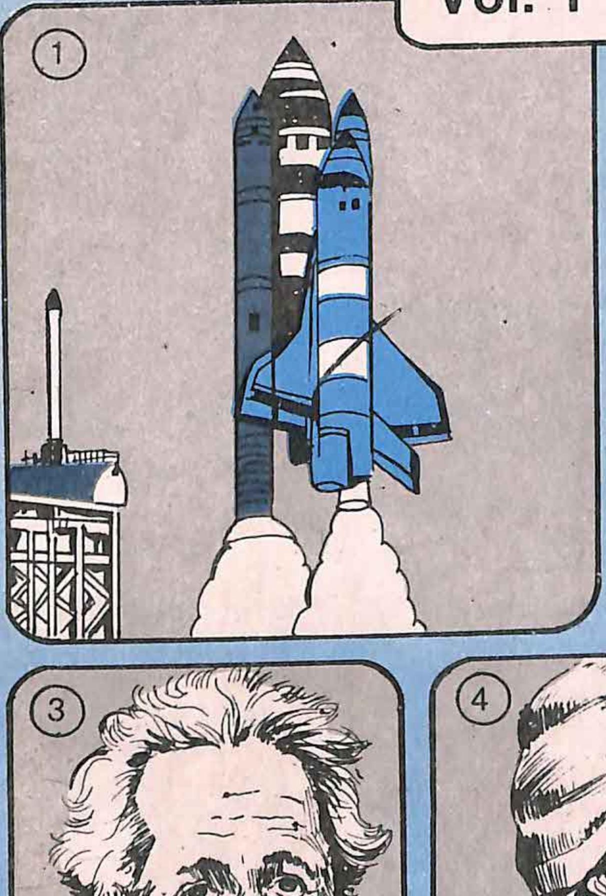
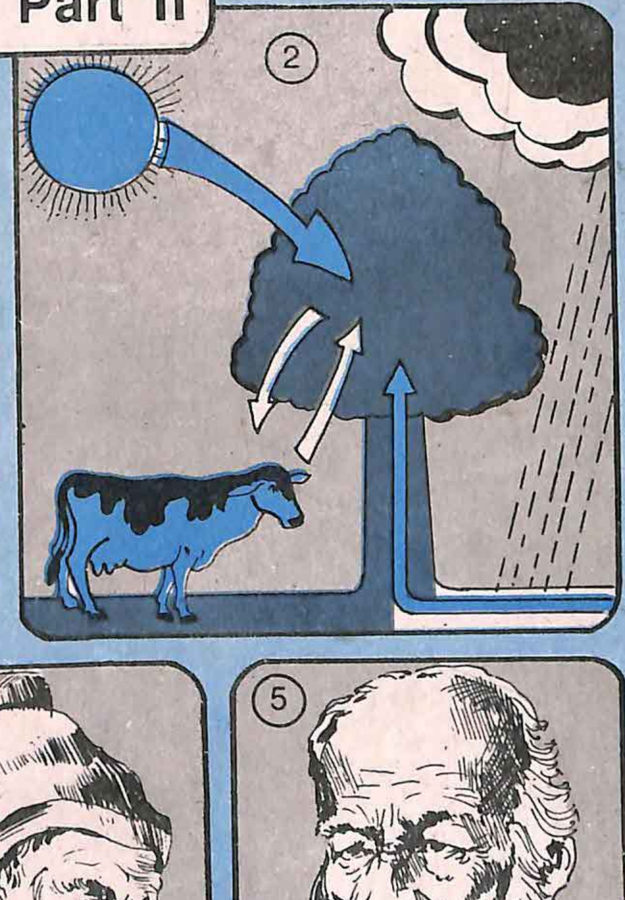
FUNDAMENTALS OF SCIENCE

Vol. I Part II





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FUNDAMENTALS OF SCIENCE

VOL. I Part II

(Covering Unit 2—Motion, Force & Energy)

(For Class IX)

By

K.K. MOHINDROO

M.Sc., B.Ed., Dip. Ed. (U.K)

Principal,
Air Force Bal Bharati School,
Lodhi Road, New Delhi
Formerly, Head of the Physics Deptt.,
Modern School, Barakhamba Road,
New Delhi

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PREFACE

For the last few years there has been growing awareness in the country that if our students are to be given useful knowldege of contemporary science, the syllabi need updating. The learning period remaining the same, a fresh approach has to be made to cope with the exponential growth of the subject. The Central Board of Secondary Education, New Delhi has introduced a new course in Science in the secondary school curriculum which would cultivate scientific temper and scientific thinking. It is with this aim in view that the present book **Fundamentals of Science** for Class IX course for the academic stream of the 10+2 pattern of education has been written. The book has been written after long and direct contact of about 31 years with the students of science and in this period of contract, I had the privilege to come across the actual problems confronting the students. A sincere and strenuous effort has been put in.

The subject matter included in this book is in accordance with the new syllabus. Each chapter in the book is self-contained and comprehensive. The material included in the book is in conformity with the trend of the new scheme i.e. to introduce a more basic approach to the study of science from the point of view of clarity, comprehension and application.

SI and c.g.s. systems of units have been used throughout. Many solved examples and unsolved problems are given in SI system. The questions at the end of each chapter have been framed which would keep the students'mind always active—an approach which is quite averse to the traditional one.

The symbols used in the book have been selected mainly in conformity with the recommendations of N.C.E.R.T. and C.B.S.E. Other *special features* of this book are:

(*i*) Language is simple and lucid.
(*ii*) Diagrams are clear, neat, well-illustrated and accurately drawn.
(*iii*) The style of the book and quality of content is such that it would lead the student to better understanding and he would gain self-confidence, and would *abhor hankering after cheap books which give memory courses only*. The students would be able to *face the examinations with confidence*.
(*iv*) Greater emphasis has been laid on basic concepts.
(*v*) The book will increase the students' ability and willingness *to inquire* for themselves.

The aim of the book is, however, not to replace the teacher. The teacher in the classroom can always train a young pupil on proper lines; the present book is to serve as an aid for this purpose.

I am thankful to several of my colleagues from Public Schools, Central Schools, Government and Aided Schools, friends and students for their valuable suggestions, criticism and help in the preparation of this book. I shall feel greatly obliged to those readers who will bring to my notice the errors and shortcomings of the book and forward to me their suggestions for its improvement.

In the end, I sincerely thank M/s Pitambar Publishing Company Pvt. Ltd. for publishing this book in a very short span of time.

K.K. MOHINDROO

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UNIT 2 MOTION, FORCE AND ENERGY

CHAPTER –1

DESCRIBING MOTION

LEARNING OBJECTIVES :

At the completion of this chapter, you should be able to grasp :

1. The concept of motion; motion and rest are relative terms; all motion is relative and there is nothing like absolute motion or absolute rest.
2. The distinction between distance and displacement.
3. The concept of speed of a body; instantaneous speed; average speed and uniform speed.
4. The difference between uniform motion and non-uniform motion.
5. The concept of graphs and their uses.
6. Distance-time graph of motion. If the distance-time graph is a straight line, the motion is uniform. The *slope* of the graph gives the speed of the body.
7. Speed-time graph of a body in motion. The *area* under the speed-time graph gives the *distance* travelled by the body during the given time interval.
8. The concept of velocity of a body; uniform velocity and variable velocity.
9. The distinction between scalar quantities and vector quantities like distance and displacement; speed and velocity etc.
10. The concept of acceleration; uniform acceleration and non-uniform acceleration.
11. Velocity-time graph of uniformly accelerated motion in a straight line. The *slope* of velocity-time graph determines the *acceleration*.
12. The concept of motion in a circle at constant speed. It is an example of accelerated motion. The acceleration being due to only the change in the direction of the velocity, its magnitude (speed) remains constant.
13. The concept of angular velocity and its relation with speed.
14. Equations of uniformly accelerated motion in a straight line–*graphically* (or otherwise).

1.1 MOTION

In our daily life we see many objects moving–a boy walking along a road, a cricketer or an athlete running on the playground; a man cycling ; a speeding Maruti car ; moving dogs, a flying bird ; a football rolling on the ground ; Air–India (a jet plane)

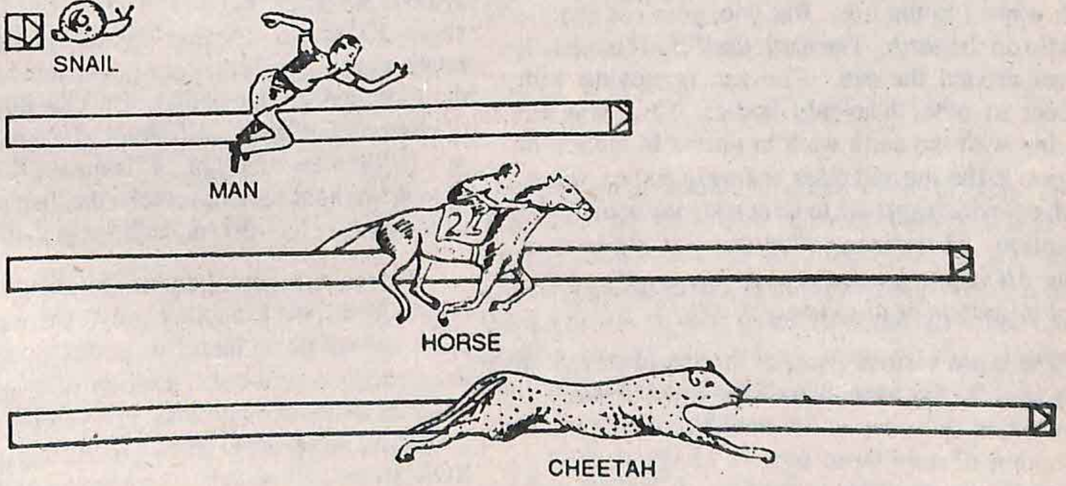

Fig. 1-1 Motion

flying in the air ; a cheetah leaping in the jungle; a satellite circling around the earth ; a ball dropping from a height ; the moon going around the earth ; the sun appearing to go across the sky ; the air particles moving in a field etc. In all these examples and in several others, which you come across in everyday life, there is something common to all of them. If you observe them for a certain interval of time, they keep changing their position with respect to other objects, some moving *slowly* and some moving *fast*.

You are travelling in a moving train. There are many other passengers in your compartment. Is there any change in your position with respect to other passengers even though you are moving with the train ? Look at nearby trees or telegraph posts outside. What do you observe ?

The continuous change of position of a body with respect to another is called **motion**.

Whenever a body does not change its position with respect to another, it is said to be at *rest*. In our daily life we see many objects which appear to be at rest. For example, an inkpot lying on a table ; a chair lying in a room ; a painting hung on the wall, a cot lying on the floor etc., are all examples of bodies at rest.

Suppose you are sitting on a cot under a tree near your house. You may be thinking that you are at rest with respect to the tree. But you, your cot and the tree lie on the earth. The earth itself is not at rest, it moves around the sun. The sun is moving with respect to other heavenly bodies. Thus you are moving with the earth wich in turn is in motion in relation to the sun and other heavenly bodies. Thus, an object which appears to be at rest may actually be in motion. *Therefore, motion and rest are relative terms. All motion is relative and there is nothing like absolute motion or absolute rest. Why ?*

There are various types of motion observed in everyday life. Try to enumerate few types of motion! However, in this chapter we shall learn to describe the motion of only those objects which move in a *straight line* — **rectilinear motion**. An athlete running on a straight track ; an aeroplane running on a straight runway ; a truck moving on a straight highway are some of the examples of this type of motion.

1.2 DISTANCE AND DISPLACEMENT

As the motion of a body is not absolute but it is relative so we describe the motion of a body by specifying its position at any instant of time with respect to a *fixed reference point* called the *origin*.

Consider a car travelling along a straight stretch of road (Fig. 1.2). At regular intervals of 100 m, there are posted observers to record the times at which the car passes so that a complete record of the motion can be obtained. The car starts opposite one observer who may be called the *reference* observer and labelled O. All time measurements are synchronized with him, and it is convenient to measure time from the instant the car starts. Thus for observer O, t = 0 and the times recorded by the other observers are the times that have elapsed since the car started. In the same way, the observer O may be taken as the reference point for the positions of the others. Thus successive observers P, Q, R, ... to the right of O are said to be at positions, + 100 m, + 200 m, + 300 m, etc., and observers N, M, L, ... to the left of O are said to be at positions – 100 m, –200 m, –300 m, etc. These are the *coordinates* of the various observers along the line of the road, and may be given the symbol x. Thus $x_P = +100$ m, $x_R = +300$ m, $x_m = -200$ m, etc. The *displacement* of one observer relative to another is the coordinate of the first minus the coordinate of the second. Thus the displacement of observer P relative to observer M is $x_P - x_M = +100$ m – (–200 m) = + 300 m. This means that P is 300 m to the right of M. Conversely, the displacement of M relative to P is – 300 m, since M is to the left of P.

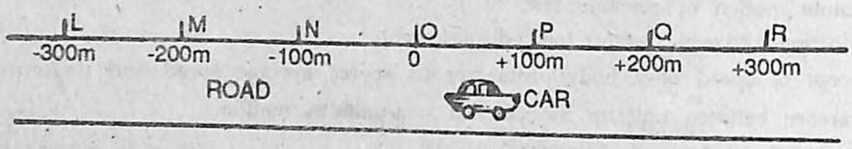

Fig. 1.2

This is one way of describing the position of a body with respect to another body. There are various other ways of doing this also. For example, suppose we want to describe the position of a hockey ball lying on the hockey ground at some point H (Fig. 1.3). Take any point O on the ground and draw a line XOX′ passing through it. The position of the hockey ball can be described precisely by measuring the

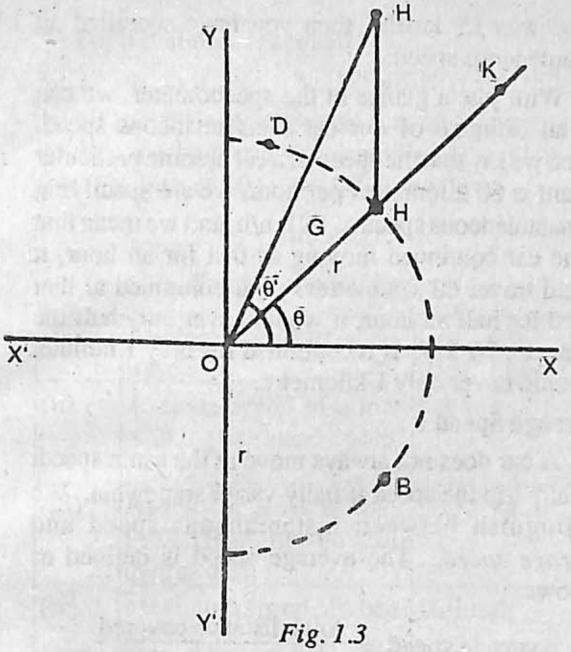

Fig. 1.3

distance OH and the angle XOH = θ, that the line OH makes with the line OX. What would happen if we only know either the angle θ or the distance r between O and H ? We note that we need two measurements to describe the position of the hockey ball H. If we are given only one of the two quantities, then the position of the hockey ball is not fully specified.

If only θ is known then the ball may be at G, H, K, ... and if only r is known then it may be at B, H, D, etc.

If the hockey ball moves from point H to another point H_1, its new position will be given by the distance between the points O and H_1 and the angle θ′ between the lines OH_1 and OX. We express this by saying that the position of a point is defined by measuring its distance from the *reference point* O and also the angle that the line joining the reference point to the given point makes with the reference axis OX. The change in position of the hockey ball from point H to point H_1 is called its *displacement*. This *displacement* is equal to the distance between the points H and H_1 measured along the direction HH_1.

Thus, in general, it follows from the above discussion that **a change of position of a particle from one point to another in a specified direction is called disaplcement.** The displacement of a body is described in terms of two quantities, *a distance* and *a direction*. The *distance* is called the *magnitude* of the displacement. It is the total length of the path travelled by the body in a certain interval of time. The displacement of a body will change if there is any change in either its magnitude or direction or both.

Suppose a body moves from a position A, at a distance x_A from the origin, to a position B at a distance x_B from the origin (Fig. 1.4) then change in

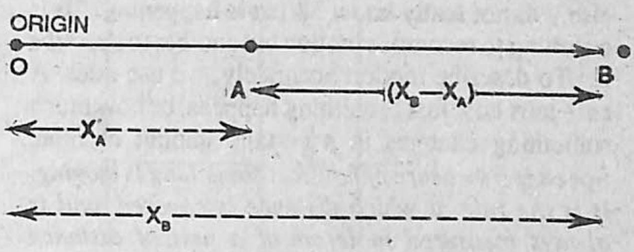

Fig. 1.4

the position is given by

$$\overrightarrow{AB} = \text{Final position} - \text{Initial position}$$
$$= OB - OA$$
$$= x_B - x_A$$

We say that the displacement $\overrightarrow{AB}$ of the body is $(x_B - x_A)$ to the right. The arrow on the top signifies that the particle has moved from A to B.

If the particle moves from B to A, then its displacement is given by

$$\overrightarrow{BA} = \text{Final position} - \text{Initial position}$$
$$= OA - OB$$
$$= x_A - x_B$$
$$= -(x_B - x_A)$$

i.e., the displacement of the body is to the left. In either case, the magnitude of the displacement is the same, *i.e.*, AB = BA but the direction in the second case is opposed to that in the first case. The sign of the displacement tells us the direction in which the body is moving. If the body moves to the *right* its displacement is *positive* but if it moves to the *left*, its displacement is *negative*.

1.3 SPEED

When we wake in the morning, it is as if our brain is asking "What's happening ?" Our mind digests the signals from our senses, and we become aware of our surroundings. Although these mental processes take place without any apparent motion, most things that "happen" around us involve things moving. Some things move fast and some slowly. To live, just to breathe and walk and talk, means motion, and the study of motion, how things move and why, is a large part of physics.

If we just say that something *moves*, someone else will not really know "What is happening?" It is one thing to recognize motion but another to *describe* it. To describe motion accurately, we use rates. A **rate** tells how fast something happens, or how much something changes in a certain amount of time. **Speed** *is a measure of how fast something is moving. It is the rate at which distance is covered, and is always measured in terms of a unit of distance divided by a unit of time.* In general,

$$\boxed{\textbf{Speed} = \frac{\text{distance}}{\text{time}}}$$

Any combination of distance and time units is legitimate for measuring speed ; for motor vehicles (or long distances) the units *kilometres per hour* (km/h) is commonly used. For shorter distances, *metres per second* (m/s) or *centimetres per second* (cm/s) are often useful units. The slash symbol (/) is read as *per* and means "divided by". Table 1.1 shows some comparative speeds in different units.

Table 1.1

Approximate speed in different units *

20	km/h	≈	333.3	m/min	≈	6 m/s
40	km/h	≈	667	m/min	≈	11 m/s
60	km/h	≈	1000	m/min	≈	17 m/s
80	km/h	≈	1333.3	m/min	≈	22 m/s
100	km/h	≈	1667	m/min	≈	28 m/s
120	km/h	≈	2000	m/min	≈	33 m/s

Instantaneous speed :

The speed that something has at any one instant is called *instantaneous speed* ; that is, how fast something was moving at one instant.

Instantaneous Speed = the rate at which something is travelling at a specific instant (or at a specific point).

If we say, "At twelve noon my bullock cart was moving at 7 km/h" or "As the bike hit the bump, its speed was 15 km/h," then you have specified an instantaneous speed.

With just a glance at the speedometer, we can get an estimate of our car's instantaneous speed. When we say that the speed of a car at some particular instant is 60 kilometres per hour, we are specifying its instantaneous speed as 60 km/h, and we mean that if the car continued moving as fast for an hour, it would travel 60 kilometres. If it continued at that speed for half an hour, it would cover only half the distance : 30 km. If it continued for only 1 minute, it would cover only 1 kilometre.

Average Speed :

A car does not always move at the same speed. On any trip the speed usually varies somewhat. We distinguish between instantaneous speed and *average speed.* The average speed is defined as follows :

$$\textbf{Average speed} = \frac{\text{total distance covered}}{\text{time taken}}$$

Suppose an athlete runs a course that is 3 kilometres long. He might sprint at the beginning but tire and slow down along the way, or even stop to tighten a shoelace, so he would not travel at the same rate for the entire 3 kilometres. But if he finishes in, say 30 minutes, then

$\frac{3\text{ km}}{30\text{ min}} = 0.10\text{ km/min} = 1.66\text{ m/s}$ is the average rate of travel during that time, or his *average speed.* If we travel 320 kilometres in 4 hours,

$$\text{Average speed} = \frac{\text{total distance covered}}{\text{time interval}}$$

$$= \frac{320\text{ km}}{4\text{ h}} = 80\text{ km/h}$$

Since average speed is the whole distance covered divided by the total time of travel, it does not indicate the different speeds and variations that may have taken place during shorter time intervals. In practice, we experience a variety of speeds on most trips, so the average speed is often quite different from the speed at any instant, the instantaneous speed. Whether we talk about average speed or instantaneous speed, we are talking about the rates at which distance is travelled.

If we know average speed and time of travel, distance travelled is easy to find. A simple rearrangement of the definition above gives

---

* It would be nice if this Chapter helps you to master these concepts, but it will be enough for you to become familiar with them and to be able to distinguish among them. The next few Chapters will sharpen your understanding of these concepts.

Total distance travelled = Average speed × time

If the car's average speed is 60 kilometres per hour on a 4 hour trip, for example, the car covers a total distance of 60 × 4 = 240 kilometres.

Table 1·2

Speeds of some objects

(i)	Average speed of a tortoise :	0.5 km/h
(ii)	Average speed of a man walking at a steady pace :	6 km/h
(iii)	Average speed of sprinter P.T. Usha in the 200 metres dash :	30.72 km/h
(iv)	Maximum speed of a bee :	16 km/h
(v)	Maximum speed of a cheetah :	96 km/h
(vi)	Maximum speed of falcon :	152 km/h
(vii)	Maximum speed of the fastest train in France :	255 km/h
(viii)	Wind speed in a light breeze :	32 km/h
(ix)	Wind speed in a hurricane :	320 km/h
(x)	The speed at which the earth goes round the sun :	107200 km/h
(xi)	Speed of light :	1.08×10^9 km/h $\approx 3 \times 10^8$ m/s

Uniform Speed (Uniform motion along a straight line) :—

When a train starts from a station, it moves very slowly in the beginning and begins to run fast for sometime. As it approaches another station, it first slows down before stopping. The motion of the train is not the same all the time.

Let us consider another example, a cricket ball dropped from the roof of a tall building. If we could measure the distance travelled by the cricket ball in successive one second intervals, we would find that the cricket ball travels larger distances in later time intervals as shown in Fig. 1.5.

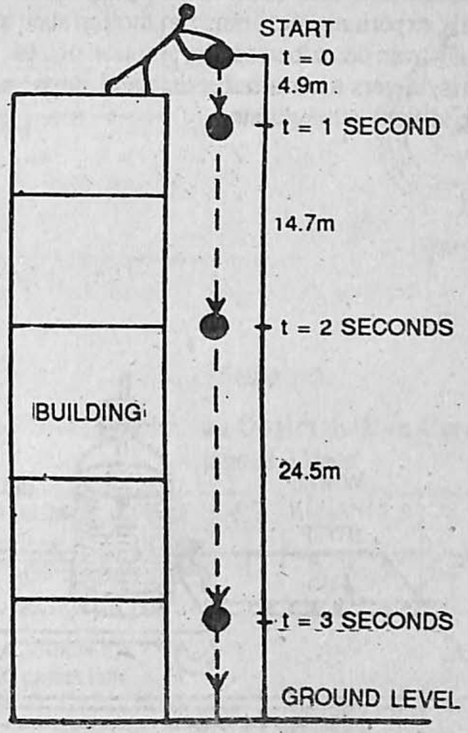

Fig. 1.5 Motion of a body along a straight line.

Another possible arrangement for studying motion in a straight line is shown in Fig. 1.6. Take a small trolly which can move freely on a smooth white paper strip on the table. A pulley is fixed at one end of the table. A string fixed to the trolly passes over the pulley and carries a weight at the other end. A small bottle fitted with a stop-cock is filled up with ink and is kept on the table as shown in Fig. 1.6. Adjust the weight in such a way that the trolly starts moving after it is pushed with a small force. Open the stop-cock slightly. Drops of ink will leave mark on the white paper. Measure the distance between these successive drops of ink. You would find that the distance between the successive drops of ink *remains the same* [Fig. 1.7(i)] and the motion of the trolly is said to be **uniform**. The distance between two successive drops is the distance covered by the trolly in the time-interval between two drops. This time-interval can be determined by counting the number of drops in, say, one minute while keeping the flow the same.

Repeat the above experiment by adding some more weight so that the trolly does not require any push to start the motion. Measure the distance between the successive drops of ink. You would find that the distance between the drops of ink does not remain the same [Fig. 1.7 (ii)] and so the motion is said to be **non-uniform**. In everyday life, we frequently experience non-uniform motion such as motion of a train described earlier; motion of a car when it starts, covers a certain distance and stops; a body dropped from a height etc.

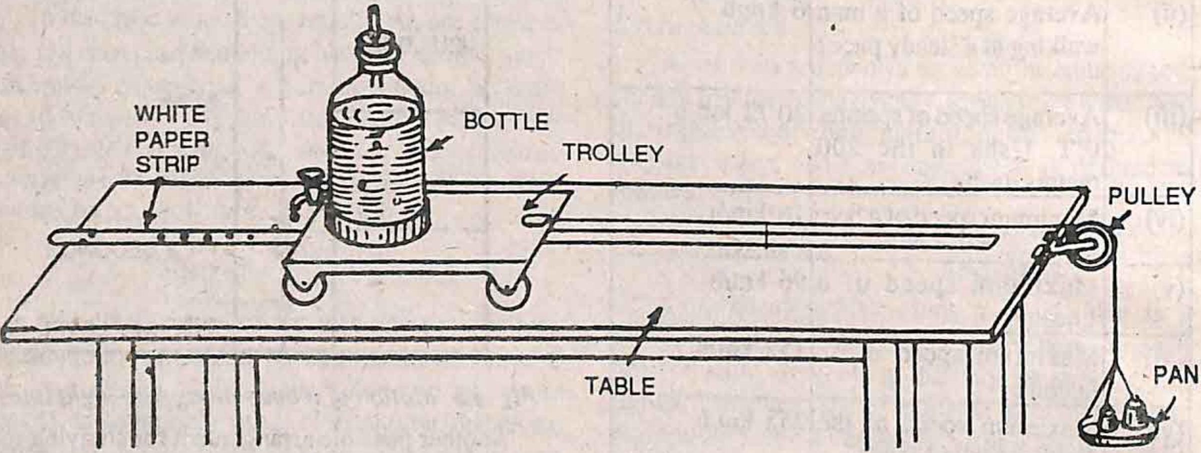

Fig. 1.6 Motion in a straight line.

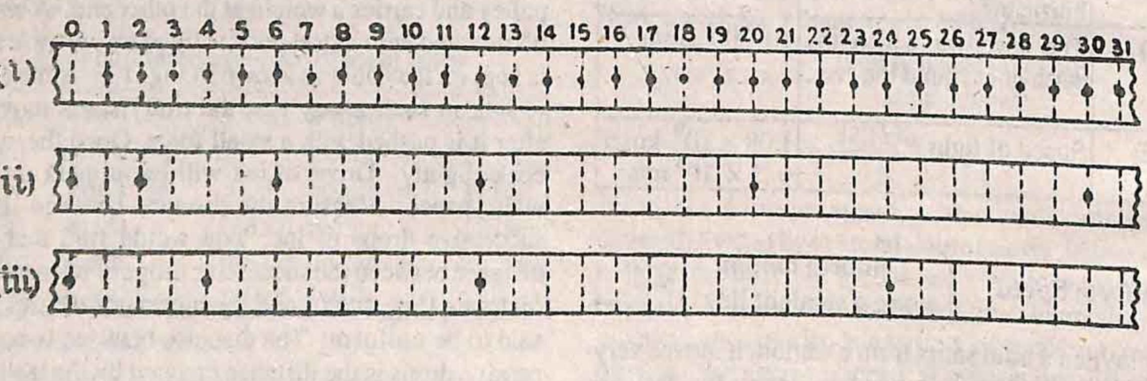

Fig. 1.7 (i) to (iii)

When a body moves over unequal distances in equal intervals of time, it possesses **non-uniform motion.**

When an object moves through equal distances in equal intervals of time, we say that it possesses **uniform motion** *and moves with* **uniform speed.** This is the special case of motion of a body along a straight line.

To predict the position of a body at any time we need a relation between distance, time and speed. Let the body move with a uniform speed υ along a straight line (Fig. 1.9). Let us measure all distances to the right of the fixed point O. If the body travels from point x_i to point x_f in time t, then

Uniform Speed (υ)

$$= \frac{\text{distance travelled}}{\text{time taken}} = \frac{x_f - x_i}{t}$$

or Distance travelled $= x_f - x_i = \upsilon t$

$$\text{or} \qquad x_f = x_i + \upsilon t \qquad \text{....... (1)}$$

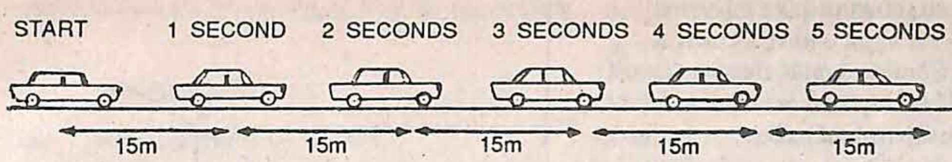

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Fig. 1.8

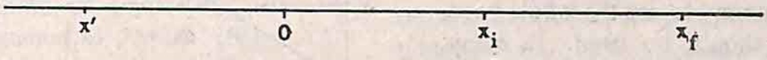


Fig. 1.9.

1.4 GRAPHS AND THEIR USES

A **graph** *is a diagram that shows the relationship between variables.* In addition to giving a "picture" of experimental results, they may be used to establish formulas and *predict new results either directly from the graph* or *by extrapolation.*

Table 1-3

Distance that an Object falls in Certain Elapsed Times

Distance in metres	0	4.9	19.6	44.2	78.5	122.6
Elapsed time in seconds	0	1	2	3	4	5

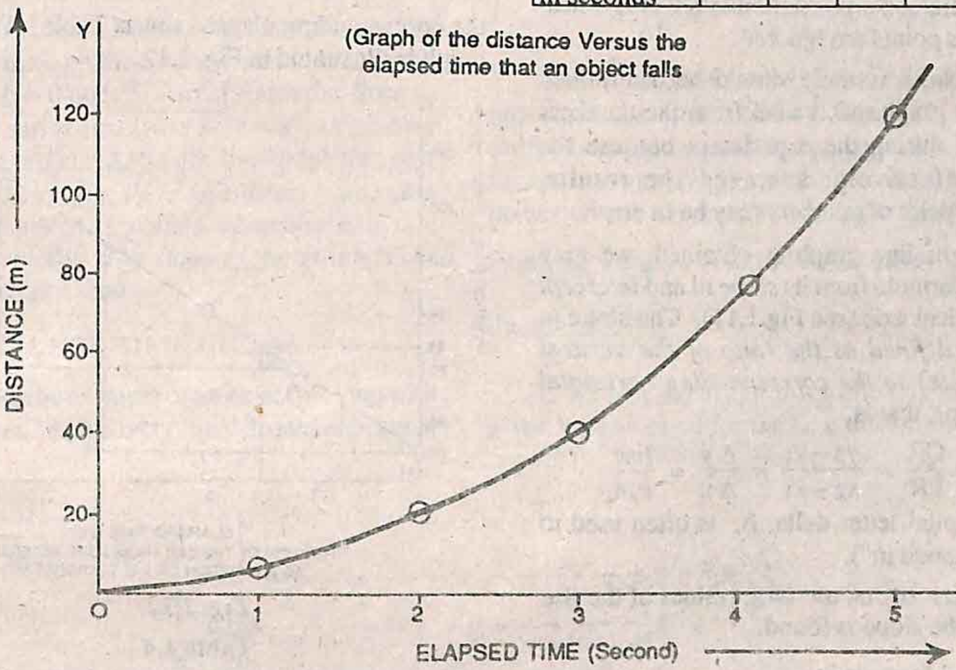


Fig. 1.10

We shall only consider graphs drawn on a Cartesian Coordinate System in which two perpendicular lines form axes. Each axis is then graduated into increments representing changes in one of the variables. A "data point" is "plotted" at the intersection of perpendicular lines from the corresponding values of the variables along the axes. A typical graph corresponding to the data in Table of observations* 1.3 is shown in Fig. 1.10.

Note that the following information should be included with the graph :

1. There should be a title indicating what the graph represents.
2. The axes should be fully labelled with numerical values and the corresponding units where applicable. The units need not be written with each numerical value provided that they are

---

* The observations of the relevant facts are set out in a tabular form called the *table of observations*.

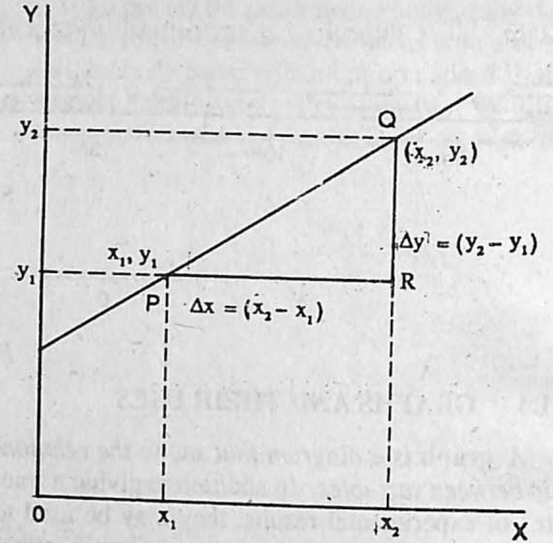
indicated under a slash showing that each value has been divided by the unit. However, when values are obtained from the graph, these units must be reinserted. *The independent variable is usually assigned the horizontal axis.*

3. The scales used on the axes should be arranged so that the graph takes up as much of the page as practical. It is not necessary to choose awkward scales merely to use the whole page; some discretion should be used. In many cases the values on the axes need not begin at zero.
4. Normally, data points should be joined by a smooth, "best-fit" line. However, on occasion one or more data points may not fall on the smooth line. Check to see if these points have been plotted correctly. If they are correct, the data may be in error, in which case these points may be noted but ignored when drawing the smooth line. Some caution is advised whenever data points are ignored.
5. If possible, a formula should be determined from the graph rather than from the numbers obtained during the experiment because the graph effectively averages the results, whereas pairs of numbers may be in error.

If a straight line graph is obtained, we may determine the formula from its *slope* m and *intercept* b with the vertical axis (see Fig.1.11). The slope m *of a graph is defined as the ratio of the vertical change* (the rise) *to the corresponding horizontal change* (the run), that is,

$$\text{Slope } m = \frac{QR}{PR} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta y}{\Delta x} = \frac{\text{rise}}{\text{run}}$$

(the Greek Capital letter delta, Δ, is often used to represent "a change in").



Graph of $y = mx + b$ where $m = \frac{\Delta y}{\Delta x}$ = slope

Fig. 1.11

To minimize errors, use large values of the rise and run when the slope is found.

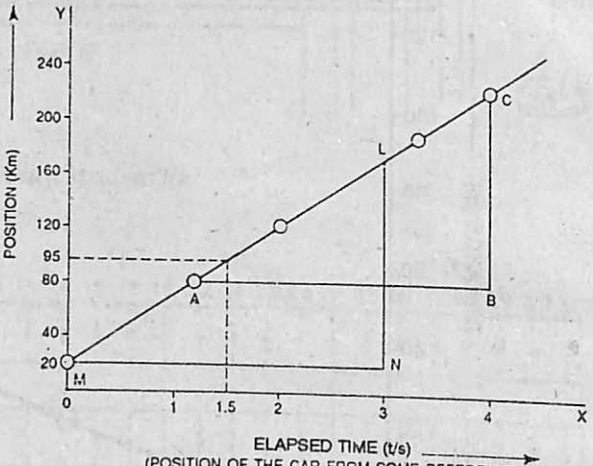
The general formula is

$$y = mx + b$$

For example, let us analyze a graph of the equation

$$d = (50 \text{ km/h})\, t + 20 \text{ km}$$

which represents the distance d of a car from some reference position as a function of the elapsed times t if it starts (at t = oh) at a point 20 km from some reference position. We shall draw the graph for a total elapsed time of 4.0 h. By substituting values for t in the equation, we may tabulate the distances and the corresponding elapsed times(Table 1.4) and the graph is illustrated in Fig. 1.12.



(POSITION OF THE CAR FROM SOME REFERENCE AS A FUNCTION OF THE ELAPSED TIME)

Fig. 1.12

Table 1.4

Position/km	20	70	120	170	220
Elapsed time/h	0	1	2	3	4

Interpretation of the graph:

Since the graph is a straight line, the *slope is constant* and it may be found between *any two points on the line:*

$$\text{Slope } m = \frac{\text{rise}}{\text{run}} = \frac{BC}{AB} = \frac{(220 - 70) \text{ km}}{3.0 \text{ h}} = 50 \text{ km/h}$$

The intercept b = 20 km ; therefore, the equation is

$$d = mt + b$$

or $$d = (50\text{ km/h})\ t + 20\text{ km}$$

which is the same as the original.

Note that other values can be read directly from the graph. For example, an elapsed time of 1.5h corresponds to a distance of 95 km (Fig. 1.12). Similarly, a distance of 145 km corresponds to an elapsed time of 2.5 h.

We can also extrapolate data by extending the line beyond the limits given in the table by assuming that the equation is still valid. Therefore, for an elapsed time of 5.0 h, we would expect a distance of 270 km, and so on. Again, some caution is advised when extrapolating data, however, because the graph may not be valid for values not indicated.

If a graph of two variables (x, y) is a *straight line* and it passes through the origin (point x = 0, y = 0), the intercept b = 0 and $\boxed{y = mx.}$ Since the slope m is constant, y varies directly as x, ($y \propto x$). Whenever we manage to produce a straight-line-graph that *passes through the origin, there is a direct proportion between that which is plotted vertically and that plotted horizontally. The slope of the graph is the proportionality constant.*

1.5 DISTANCE-TIME GRAPH

Let us take the example of an object moving with a *uniform speed,i.e.*, it covers equal distances in equal intervals of time. *The distance time graph of this object is always a straight line* (See Fig. 1.12). The distance covered by the car (from 1 h to 4 h), *i.e.*, in 3 h is represented by the length CB (Fig. 1.12). The distance covered from (0 h to 3 h); i.e., in 3h is represented by the length LN. We can check that length CB and the length LN are equal.

A straight line graph will tell us at a glance that the object moves with uniform speed ; whereas in a table we would have to calculate distances covered in successive intervals to see if they are equal.

The *speed* of a moving object can also be found from the distance time graph. For example in Fig. 1.12 the time taken to travel a distance CB (150 km) is shown by AB (3 h). We know that

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

$$= \frac{CB}{AB} = \frac{150\text{ km}}{3\text{ h}} = 50\text{ km/h}.$$

This is called the *slope of the line* (m). **We can now find the speed of any object moving with uniform speed by calculating the slope of its distance-time graph.** For uniform motion it does not matter where we draw the triangle ABC. For example, if we draw it at LNM, the ratio $\frac{LN}{NM}$ will be the same as $\frac{CB}{AB}$.

If we plot the distance travelled by a body in a given time-interval for the case of a uniform motion

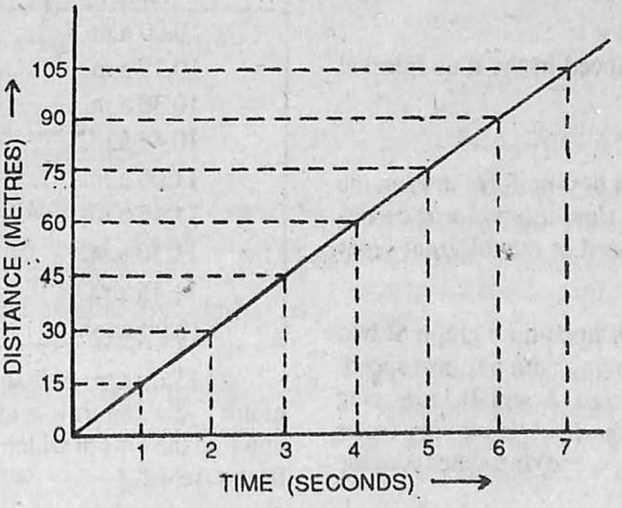


Fig. 1.13

[*e.g.*, case in Fig. 1.7(i)], we get a graph shown in Fig. 1.13. We note that distance-time graph in this case is a *straight line passing through the origin*. In this case the *average speed* in all time-intervals will be the *same*.

If we plot the distance travelled by the body in a given time-interval for the case of a *non-uniform* motion, *e.g.*, case of a cricket ball falling from a height or case of Fig. 1.7(ii), we get a graph as shown in Fig. 1.10 or Fig. 1.14. *This graph can be used to find the average speed of the body.*

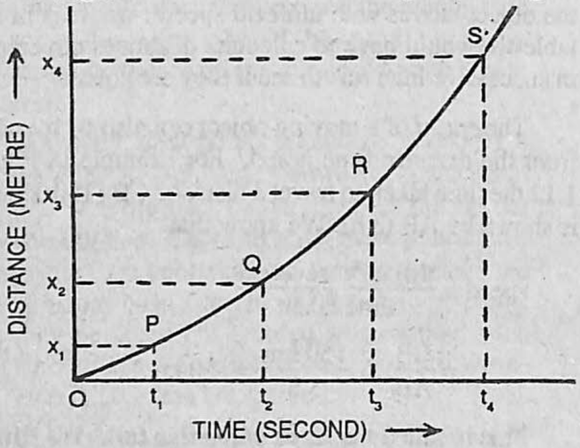


Fig. 1.14

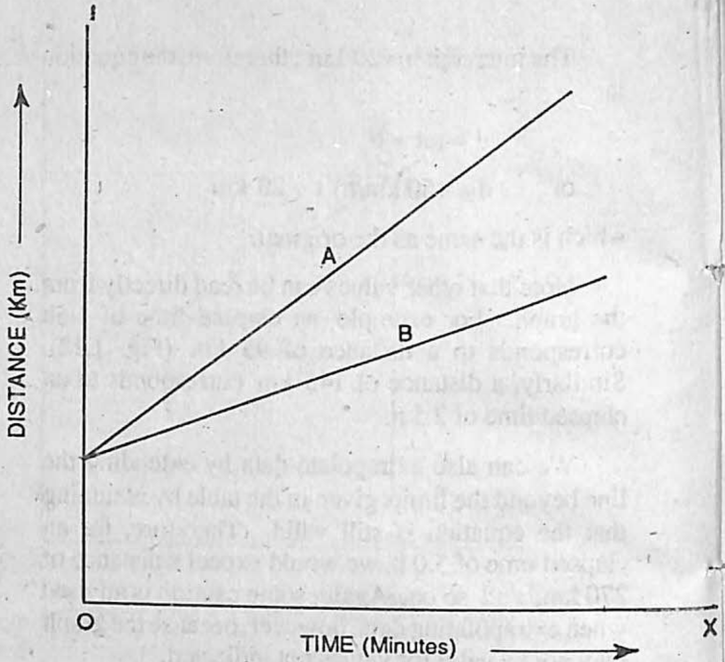
Take four points P, Q, R and S with coordinates (x_1, t_1) (x_2, t_2), (x_3, t_3) and (x_4, t_4) respectively in Fig. 1.14. The average speed in the time-interval $(t_2 - t_1)$ is $\frac{(x_2 - x_1)}{(t_2 - t_1)}$.

Similarly, the average speed in the time-interval $(t_4 - t_3)$ is $\frac{(x_4 - x_3)}{(t_4 - t_3)}$.

Again, the average speed in the time-interval $(t_4 - t_1)$ is $\frac{(x_4 - x_1)}{(t_4 - t_1)}$.

You will notice that in non-uniform motion the average speed in a certain time-interval *will be different* from the average speed in the different time-intervals.

Fig. 1.15 shows the distance-time graph of two bodies (say scooterists) moving with uniform speed. Which of the two scooterists A and B is moving faster ? Obviously the scooterist A is moving faster as the slope of graph A (*i.e.*, speed) is greater than the slope of graph B.



(DISTANCE-TIME GRAPH OF TWO SCOOTERISTS MOVING WITH UNIFORM SPEED)

Fig. 1.15.

It should now be very clear that a distance-time graph for a moving object is more efficient in describing the motion than its distance-time table. Moreover plotting a graph is even more advantageous when we want to compare the motion of the objects. In order to understand these points let us consider the following example :

Ashish started from his house at 10.00 a.m. on a bicycle. His distance-time table is given in Table 1.5.

Table 1.5

Time	*Distance*
10.00 a.m.	0 km
10.15 a.m.	4 km
10.30 a.m.	8 km
10.45 a.m.	12 km
11.00 a.m.	16 km
11.15 a.m.	20 km
11.30 a.m.	24 km
11.45 a.m.	28 km
12.00 noon	32 km

At 11.00 a.m. Ashish's friend Akram starts on a motor cycle and travels at a speed of 40 km/h. Can you find the time at which Akram catches up with his friend Ashish ?

Let us construct the distance-time table of

Akram's motion since we know that he is travelling at a uniform speed of 40 Km/h. By using the relation speed = $\frac{\text{distance}}{\text{time}}$, we can construct the following table 1.6 :

Table 1.6

Time	*Distance*
11.00 a.m.	0 km
11.15 a.m.	10 km
11.30 a.m.	20 km
11.45 a.m.	30 km
12.00 noon	40 km

These tables 1.5 and 1.6 do not directly tell us the time and place where Akram overtakes Ashish. However, if we draw distance-time graphs of the motion of Ashish and Akram [Fig. 1.6], then we can use these graphs to find (i) the time at which Akram overtakes his friend Ashish? (2) How far were they from Ashish's house when they met? (3) What was the distance separating the two friends at 11.00 a.m. and 11.37 a.m.? If Ashish had travelled at a speed 12 km/h, would Akram catch him earlier or later? If Akram had travelled at a speed greater than 40 Km/h, would he meet his friend Ashish earlier or later? (I shall advise students to draw these graphs on a graph paper and ascertain the above mentioned points by using these graphs). From Fig. 1.16 it is clear that Akram overtakes Ashish at 11.37 a.m. at a distance of 25 Km from Ashish's house. The distance separating the two friends at 11.00 a.m. and 11.37 a.m. is 10 Km.

1.6 SPEED-TIME GRAPH

We know that

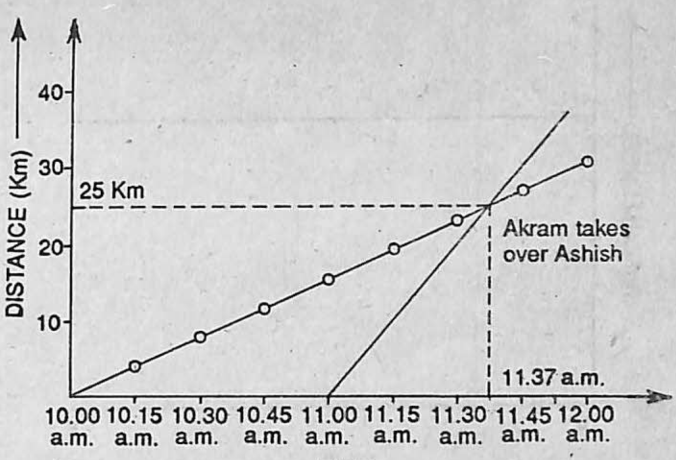
$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

$$\therefore \quad \boxed{\text{distance} = \text{speed x time}}$$

The distance can also be found using a graph of speed and time. If an object moves at *uniform speed* (v) the height of its speed-time graph will not change with time. It will be a line parallel to the x-axis as shown in Fig. 1.17.

The distance covered by this body from time t_1 to time t_2 is given by

$$\text{distance} = \text{speed} \times \text{time}$$
$$= v \times (t_2 - t_1)$$



DISTANCE-TIME GRAPH OF TWO MOTIONS

Fig. 1.16

The speed v is represented by the vertical line PQ or RS in Fig. 1.18 and the time $(t_2 - t_1)$ is represented by the horizontal line PR. Therefore, the distance travelled can also be expressed as

$$\text{Distance} = PQ \times PR$$

= Area of the rectangle PQSR (shaded portion in Fig. 1.18)

As an example, Fig. 1.19 shows the speed-time graph of a Maruti Car moving with a uniform speed of 60 Km/h. Let us find the distance travelled by it from 10.00 a.m. to 10.30 a.m. from the speed-time graph.

Since, distance travelled = Area of the rectangle PQRS

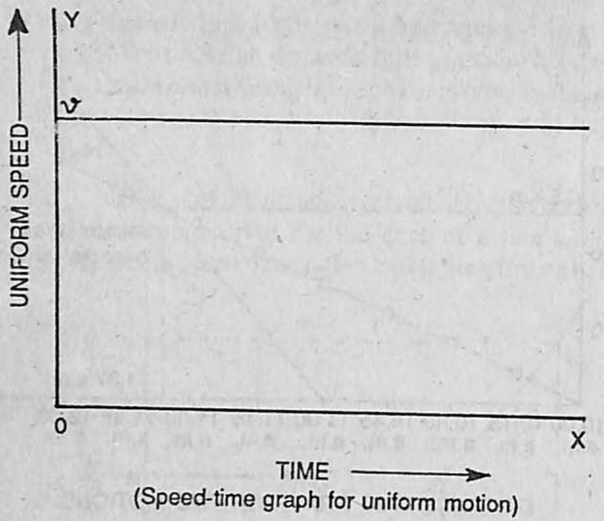
$$\therefore \text{distance} = PQ \times PR$$
$$= 60 \text{ Km/h} \times 30 \text{ min}$$
$$= 60 \text{ Km/h} \times \frac{1}{2} \text{ h} = 30 \text{ Km}$$

1.7 SCALARS AND VECTORS

In a three dimensional space there are many physical quantities that have direction as well as magnitude. Such quantities are called **Vectors.** For example displacement, velocity, acceleration, force, momentum etc.

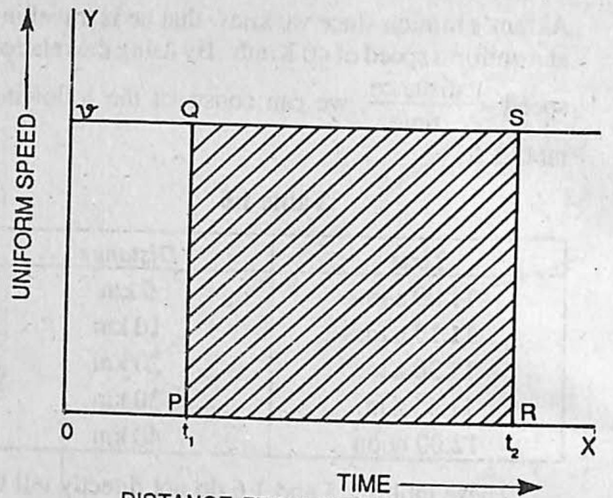
A quantity that has magnitude but no direction is called a **scalar**. Examples of scalars are time, mass, speed, temperature, electric charge, volume, density, energy, distance etc.

The magnitude of a vector, a scalar quantity is



(Speed-time graph for uniform motion)

Fig. 1.17



DISTANCE FROM SPEED-TIME-GRAPH

Fig. 1.18

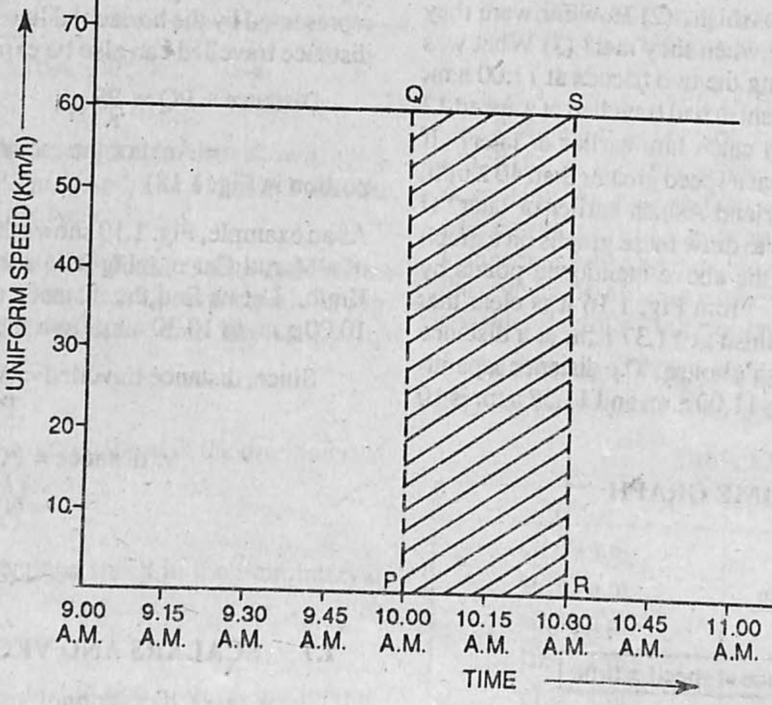


Fig. 1.19

called *modulus of the vector*. The modulus of the vector $\overrightarrow{OA}$ (Fig. 1.20) is denoted by $|\overrightarrow{OA}|$.

Symbol for a Vector. In print, the symbol for a vector is set in bold face type, whereas the symbol for a scalar is set in italics. The vector representing the displacement between A and B will be printed as AB whereas the magnitude of the displacement is printed in ordinary type, in the same mabber as scalars. The magnitude of vector AB will be printed as AB. In handwriting this distinction is difficult and it is convenient to indicate a vector quantity by placing an arrow above it; for example the magnitude of the displacement $\overrightarrow{AB}$ is, however, represented by AB or sometimes | **AB** | or | $\overrightarrow{AB}$ |.

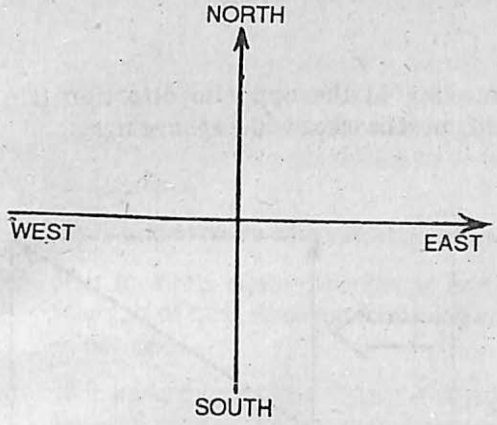


Fig. 1.20

Graphical Representation of Vectors :

A vector is represented pictorially (i.e., through a diagram) by a line that is drawn in the same direction as the vector and has a length proportional to the magnitude of the vector on some agreed scale. An arrowhead indicates one of the two possible directions along the line.

Suppose we want to represent a displacement of 30 km of a body from west to east. If 1 cm is chosen to represent a displacement of 10 km, a line OA, 3cm long and drawn from west to east, with arrow-head at A (Fig. 1.20) will represent completely the displacement of the body. The end where the arrowhead is marked is called the **head** of the vector, whereas the other end is called the **tail** of the vector. Thus in (Fig. 1.20), A is the head and O is the tail of the vector $\overrightarrow{OA}$.

Similarly a displacement of 60 km from south to north could be represented by a line CD from south to north with an arrow-head pointing due north and a length of 6 cm, if it had been agreed that 1 cm was to represent 10 km (Fig. 1.21).

The **negative** of a vector is defined as another vector having the same length but drawn in opposite direction. Thus in (Fig. 1.22) the vector $\overrightarrow{PQ}$ is equal in length but opposite in direction to vector $\overrightarrow{QP}$. In other words, the displacements shown in (Fig. 1.22) are not the same, though their magnitudes are equal.

Hence negative of the vector $\overrightarrow{PQ}$ is $\overrightarrow{QP}$. This is represented by the following relation :

$$\overrightarrow{PQ} = -\overrightarrow{QP}$$

or $$\overrightarrow{QP} = -\overrightarrow{PQ}$$

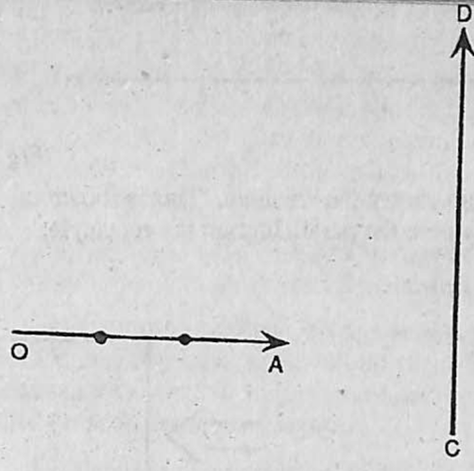


Fig. 1.21

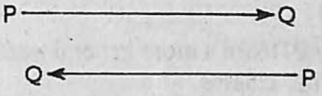


Fig. 1.22

Equal Vectors :

Two vectors of the same physical quantity are **equal** if they have the same magnitude and drawn in the same direction. Fig. 1.23 shows two vectors $\overrightarrow{AB}$ and $\overrightarrow{CD}$ which have the same length and are drawn along the same direction. Hence they are equal, wherever they may be drawn.

It follows that two equal vectors are represented by directed lines of *equal* lengths *parallel* to each other. *Thus an important property of vectors is that a vector can always be displaced parallel to itself without in anyway changing it.*

Adding Vectors :

Adding Vectors that act along parallel directions is simple enough : if they are in the *same direction*, they *add* ; if they are in *opposite directions*, they *subtract*. The sum of two or more Vectors is called their *resultant*. To find the resultant of two Vectors that are at angles to each other, we use the **parallelogram rule.** Construct a *parallelogram* wherein the two vectors are adjacent sides ; the diagonal of the

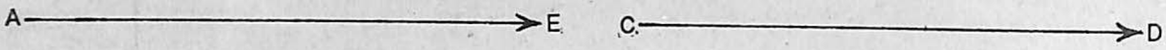


Fig. 1.23

parallelogram shows the resultant. This is shown in Fig. 1.24 where the parallelogram is a rectangle.

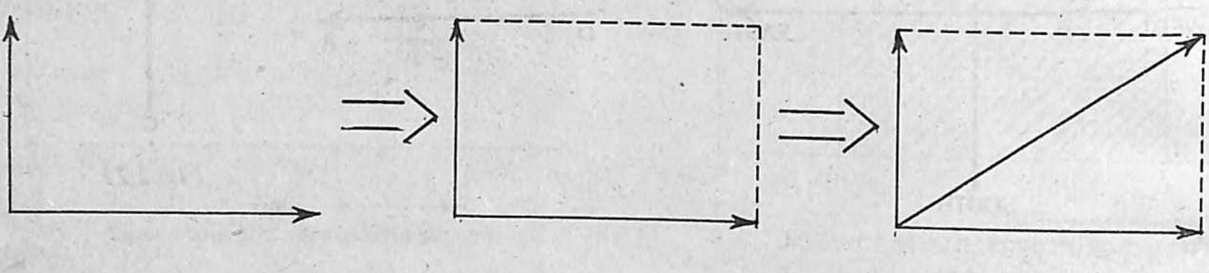


Fig. 1.24

You will learn a more general treatment of vectors in higher classes.

1.8 VELOCITY

When a bus moves along a road, its speed is in a certain direction. If we wish to combine the two concepts, speed and direction, we are speaking of a vector. This vector is called the **velocity** of the bus. For example, if we say that a bus is travelling at 30 km/h, we are giving the speed of the bus. If we say that the bus is travelling 30 km/h eastward, we are giving the bus' velocity. Knowledge of the speed of the bus alone does not tell us where the bus will be after some time. At the end of a few minutes, the bus may be back on the same spot from where it started. Though the bus ran very fast, at the end, its displacement is zero. Thus it is important to make use of the vector nature of velocity of a body. Velocity, the vector, is related to speed in the same way that displacement is related to distance.

The velocity of a moving body is the rate of change of position of the body in a particular direction.

The velocity of a moving body may also be defined as its speed in a particular direction.

Thus velocity possesses magnitude as well as direction. The magnitude of the velocity is speed. Any change either in the magnitude or the direction or both will change the velocity of the body. If the velocity of a body moving in a particular direction (say eastward) is taken with *positive sign*, its velocity when moving in the opposite direction (say westward) must be taken with *negative sign.*

Since velocity of a body is displacement per unit time so if a body undergoes a displacement $\vec{s}$, in a time-interval, t, then its velocity $\vec{v}$ is given by

$$\boxed{\vec{v} = \frac{\vec{s}}{t}} \quad \text{.... (1)}$$

Units :

The units of velocity are the same as those of speed

i.e., **m/s (or $\mathbf{ms^{-1}}$) ; cm/s (or $\mathbf{cms^{-1}}$) ; km/h (or $\mathbf{kmh^{-1}}$).**

Suppose that the Rajdhani Express traverses a distance of 60 km in one hour towards north, then, its

$$\text{velocity} = \frac{\text{distance}}{\text{time}}$$

$$= \frac{60 \text{ km}}{\text{one hour}} = 60 \text{ km/h towards north}$$

$$= \frac{60 \times 1000}{60 \times 60} \text{ ms}^{-1}$$

$$= 16.6 \text{ ms}^{-1} \text{ towards north}$$

If a body not only traverses equal distances in equal intervals of time, however, small these intervals may be, but also continues to move in the same direction, it is said to possess **uniform velocity.**

The equation (1) will hold provided the rate of change of displacement during the time-interval, t, is *uniform.*

In practice, however, the velocity of a body is seldom uniform over large periods of time. The earth is no doubt rotating with a uniform speed about its axis but at every instant it is changing its direction. Its velocity is, therefore, not uniform but *variable*. Similarly, the speed as well as the direction of an aeroplane may undergo changes during its journey between two airports.

A body is said to move with *variable velocity*.

(*i*) If it traverses equal distances is unequal intervals of time, direction remaining same or not, or

(*ii*) If it traverses unequal distances in equal intervals of time, direction remaining same or not, or

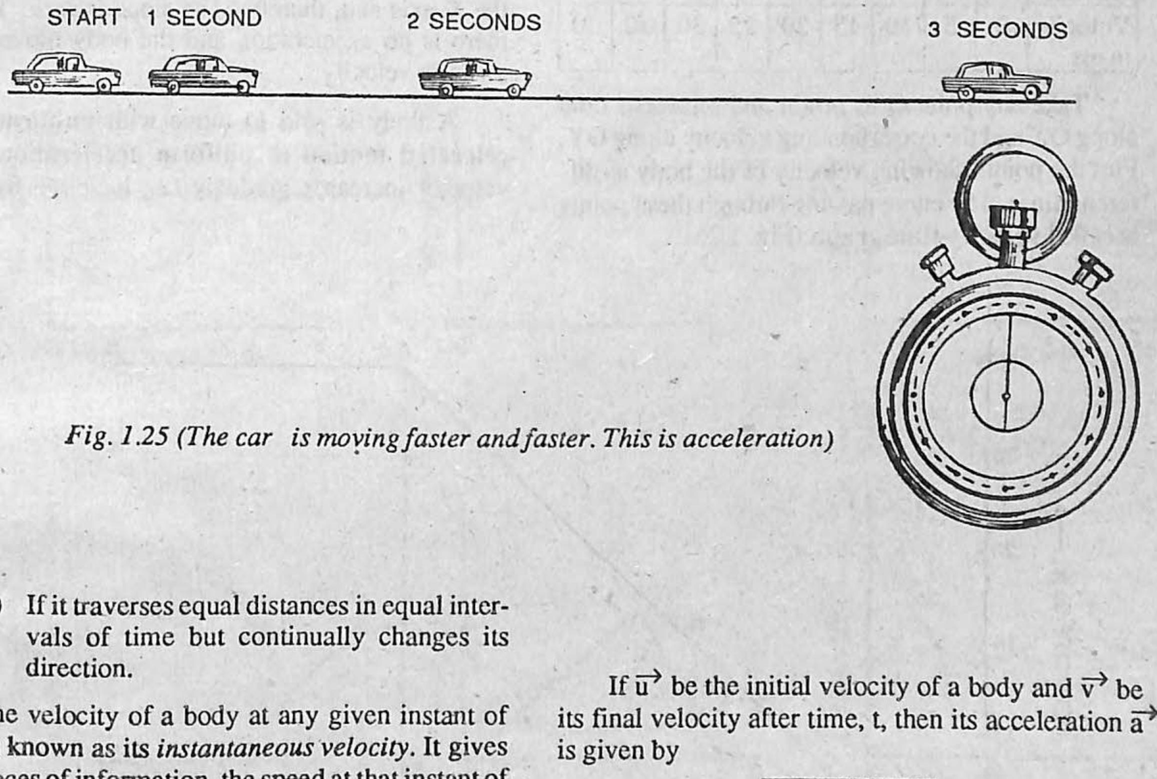


Fig. 1.25 (The car is moving faster and faster. This is acceleration)

(iii) If it traverses equal distances in equal intervals of time but continually changes its direction.

The velocity of a body at any given instant of time is known as its *instantaneous velocity*. It gives two pieces of information, the speed at that instant of time and the direction of motion at that instant of time.

1.9 ACCELERATION (NON-UNIFORM MOTION)

If an object is not moving at a constant speed in a straight line (that is if the velocity is not constant), it is said to be **accelerating**. Remember that the term velocity includes direction. There are two extreme categories of situations involving accelerating motion : Motion along a straight line at a changing speed, and motion at constant speed but with changing direction. The two, of course, could be combined.

Acceleration is defined as the rate of change of velocity i.e., change in velocity per unit time.

If the velocity increases, the acceleration is *positive*. On the other hand, if the velocity decreases, the acceleration is negative. Negative acceleration is also called **retardation or deceleration.**

Acceleration is a *vector* quantity as it involves magnitude as well as direction.

Acceleration (along a straight line)

$$= \frac{\text{Change in velocity}}{\text{Time taken}}$$

If $\vec{u}$ be the initial velocity of a body and $\vec{v}$ be its final velocity after time, t, then its acceleration $\vec{a}$ is given by

$$\boxed{\vec{a} = \frac{\vec{v} - \vec{u}}{t}}$$

The **unit** of acceleration is $\frac{\text{Unit of velocity}}{\text{Unit of time}}$. If velocity is expressed in m/s, then the unit of acceleration is m/s^2 or ms^{-2}. It is read as metre per second square or metre per second per second. Other unit is cm/s^2 or cms^{-2}

The earth attracts every body lying on or near its surface towards its centre and the acceleration produced in the body is known as *acceleration due to gravity* (g). Its value is 9.8 ms^{-2} ≈ 10 ms^{-2}. If a body moves vertically upwards, then its acceleration is –9.8 ms^{-2}.

1.10 VELOCITY-TIME GRAPH

The nature of motion of a body can be better depicted by means of graphs.

Let us consider the motion of a body whose velocity at different times is given below :

Time in seconds	0	2	4	6	8	10	12	14	16
Velocity in ms^{-2}	0	5	10	15	20	25	30	30	30

Take any point O as origin and represent time along OX and the corresponding velocity along OY. Plot the points showing velocity of the body at different times. The curve passing through these points is called **velocity-time graph** (Fig. 1.26).

The graph consists of two parts OA and AB. The part OA shows that the velocity increases with time. The ratio $\frac{MA}{OM}$ or $\frac{NP}{ON}$ is called the **slope** of the curve. Since NP is increase in velocity in time ON, therefore, $\frac{NP}{ON}$ measures the rate of change of velocity or acceleration. *Thus, the acceleration is given by the slope of the velocity-time graph.*

Since $\frac{NP}{ON} = \frac{MA}{OM}$, it is clear that the acceleration is *uniform* in the part OA of the curve. During the time OM, the body is said to have **uniformly accelerated motion**. The graph OA between velocity and time for uniformly accelerated motion is a *straight line*.

The second part of the curve, AB, is parallel to the X-axis and, therefore, its slope is *zero*. Hence, there is no acceleration and the body moves with uniform velocity.

A body is said to move with **uniformly accelerated motion** or **uniform acceleration** if its velocity increases gradualy *i.e.*, increases by equal

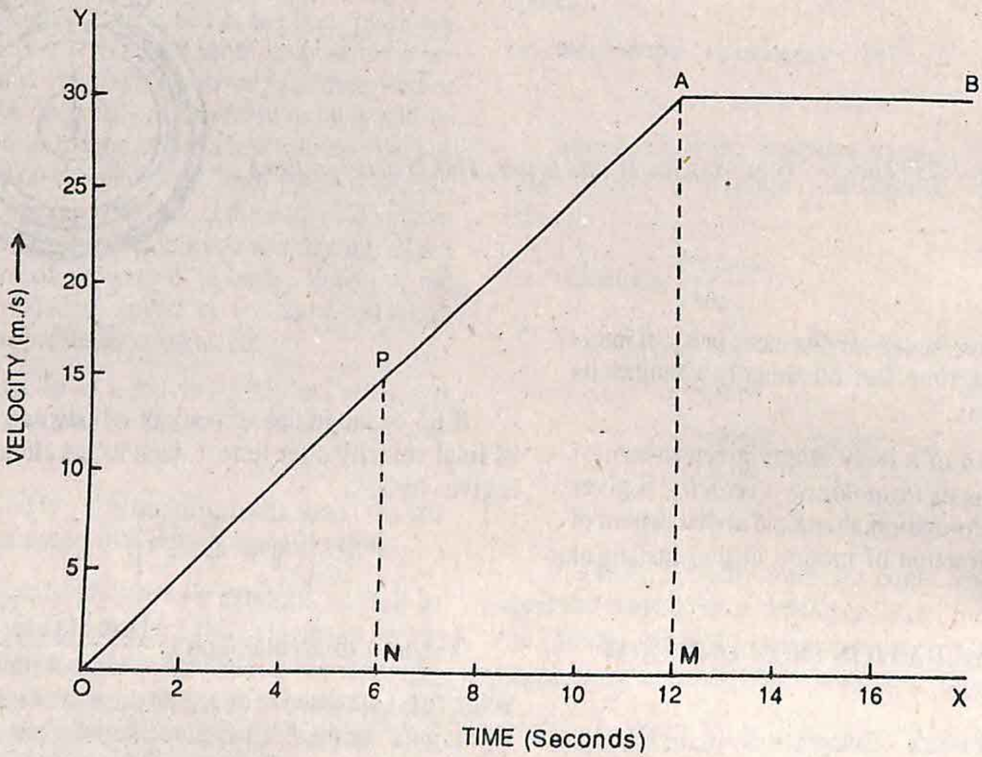


Fig. 1.26

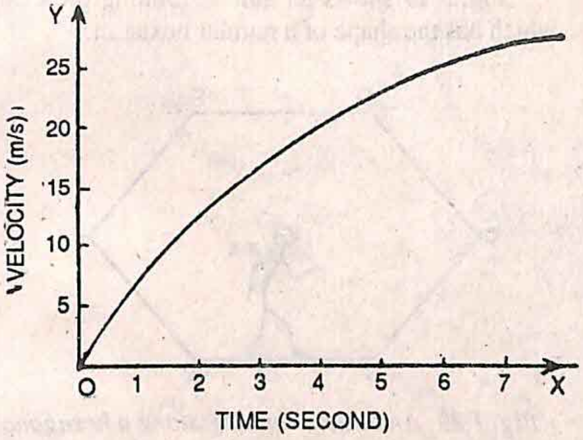


Fig. 1.27 Non-uniformly accelerated motion.

amounts in equal intervals of time, however small these intervals may be.

Examples of uniformly accelerated motion are :

(*i*) A body falling freely under the action of gravity.

(*ii*) Motion of a scooter going down the road on a hill when the petrol is off and the air resistance is negligible.

(*iii*) A steel ball rolling down an inclined plate of glass.

(*iv*) A moving car whose speed increases equally in equal intervals of time along a straight road.

A body is said to move with **non-uniformly accelerated motion** if its change in velocity in successive equal intervals of time may not be the same. The velocity-time graph for such a motion may have any shape (other than a straight line) as shown in Fig. 1.27.

Let us discuss some more velocity-time graphs as shown in Fig. 1.28.

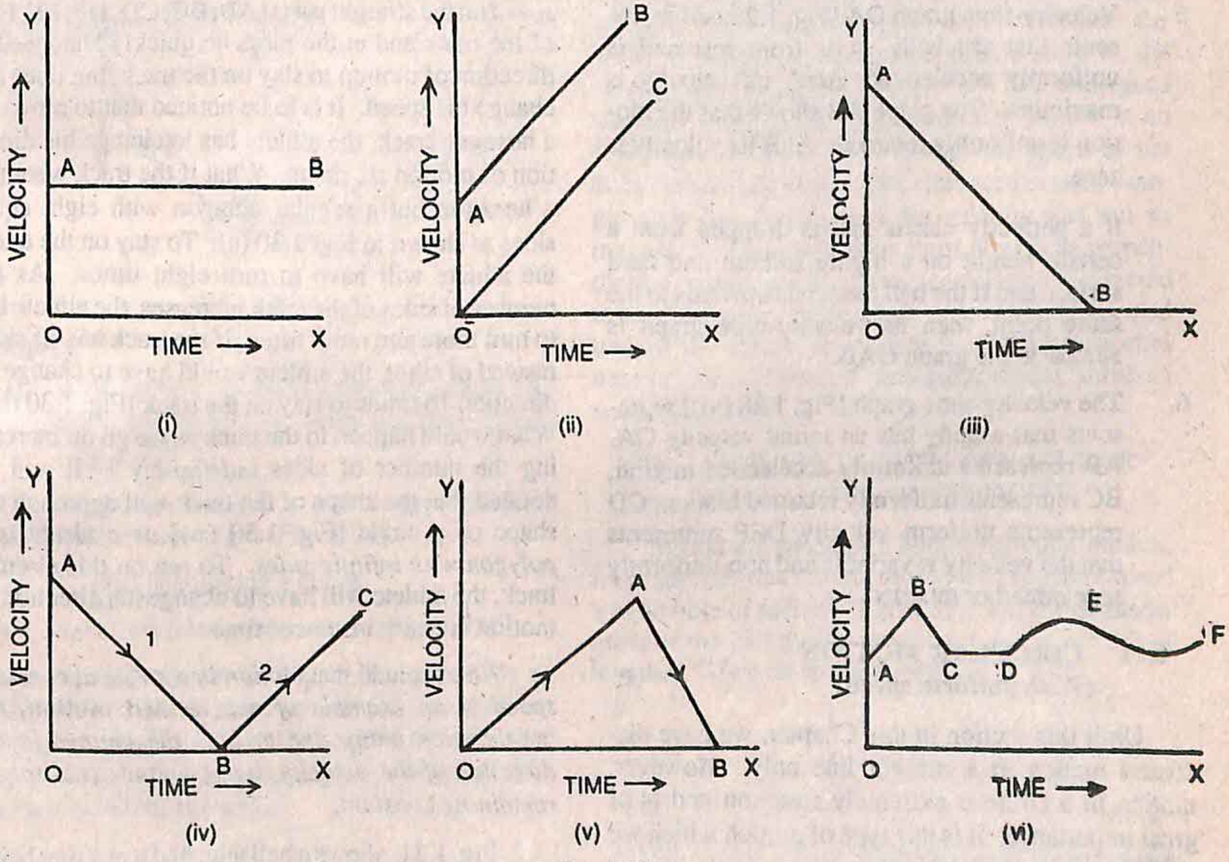


Fig. 1.28

1. Velocity-time graph AB [Fig. 1.28 (i)] represents that the body has uniform velocity throughout its motion.

2. Velocity-time graph AB [Fig. 1.28 (ii)] represents that a body has some initial velocity OA

and it is moving with uniform acceleration.

The graph OC represents that the body starts from rest and it is moving with uniform acceleration.

3. Velocity-time graph [Fig. 1.28 (iii)] represents that the body has some initial velocity OA and it is moving with uniform retardation (negative acceleration).

4. Velocity-time graph AB [Fig. 1.28 (iv)] represents that the body has an initial velocity OA and it is moving with uniform retardation. At the point B, the velocity of the body is zero. The graph BC represents that the body is uniformly accelerated. If a body is projected vertically upwards with some initial velocity and it comes back to the same point, velocity-time graph is similar to the graph ABC.

5. Velocity-time graph OA [Fig. 1.28 (v)] represents that the body starts from rest and is uniformly accelerated. At A its velocity is maximum. The graph AB shows that the motion is uniformly retarded. At B its velocity is zero.

   If a perfectly elastic ball is dropped from a certain height on a highly smooth and hard surface and if the ball rebounds upwards to the same point, then its velocity-time graph is similar to the graph OAB.

6. The velocity-time graph [Fig. 1.28 (vi)] represents that a body has an initial velocity OA. AB represents uniformly accelerated motion, BC represents uniformly retarded motion, CD represents uniform velocity, DEF represents that the velocity is variable and non-uniformly accelerated or retarded.

1.11 CIRCULAR MOTION
(With uniform speed)

Until this section in this Chapter, we have discussed motion in a straight line only. However, motion in a circle is extremely common and is of great importance. It is this type of motion which we shall discuss in this section.

When the velocity of an object changes we say that the object is accelerating. This change could be a change in the speed or a change in its direction of motion or both. Can we think of an example where an object does not change its speed but only its direction of motion? Let us study an example of this type of motion.

Fig. 1.29 shows an athlete running on a track which has the shape of a regular hexagon.

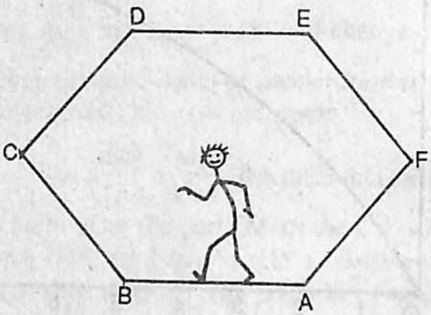
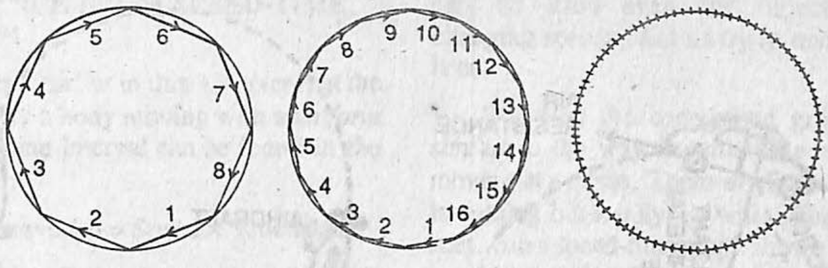


Fig. 1.29 An athlete running along a hexagonal track.

Let us assume that the athlete runs at *uniform speed* on the straight parts (AB, BC, CD, DE, EF, FA) of the track and at the turns he quickly changes his direction of motion to stay on the track, but does not change his speed. It is to be noticed that to move on a hexagon track, the athlete has to change his direction of motion *six* times. What if the track were not a hexagon but a regular octagon with eight equal sides as shown in Fig. 1.30 (a). To stay on the track, the athlete will have to turn eight times. As the number of sides of the track increases, the athlete has to turn more and more often. If the track has 16 sides instead of eight, the athlete would have to change its direction 16 times to stay on the track [Fig. 1.30 (b)]. What would happen to the track as we go on increasing the number of sides *indefinitely* ? It will be noticed that the shape of the track will approach the shape of a circle [Fig. 1.30 (c)] *as a circle is a polygon with infinite sides.* To run on this circular track, the athlete will have to change his direction of motion at every instant of time.

We conclude that *motion in a circle at constant speed is an example of* **accelerated motion**, *the acceleration being due to only the change in the direction of the velocity, its magnitude (i.e., speed) remaining constant.*

Fig. 1.31 shows a ball attached to a string being whirled round in a horizontal circle. The ball moves with a uniform speed in a circular path of radius OP about O. Such motion is **uniform circular motion**, or *the motion of an object at constant speed along a curved path of constant radius.*



POLYGON OF 8 SIDES (a)

POLYGON OF 16 SIDES (b)

POLYGON OF INFINITE SIDES (CIRCULAR TRACK) (c)

Fig. 1.30

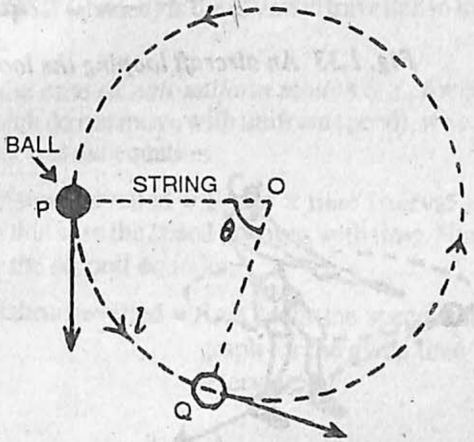


Fig. 1.31

Examples

(i) A car travelling round a circular bend on a perfectly level road with uniform speed (Fig. 1.32)

(ii) Whirling a hammer in a circle by an athlete before throwing it (Fig. 1.34).

(iii) Cyclist negotiating a curve.

(iv) An aircraft looping the loop (Fig. 1.33).

As the ball shown in Fig. 1.31 moves in a circular path with *constant* speed, its direction is continually changing. P and Q represent two successive positions of the ball moving with uniform circular motion about point O.

The velocity vector $\vec{V}_P$ indicates the velocity of the ball when at point P, and the velocity vector $\vec{V}_Q$ indicates its velocity at point Q. The velocity vectors are tangents to the circle respectively at P and Q, and are thus perpendicular to the respective radii OP and OQ. If the ball is released when it is at P, it will fly off along the tangent to the circle at P. Similarly, if the ball is at Q when released, it will fly off along the tangent at Q. *Thus while the velocity of the ball does not change in magnitude, it does change in direction.* **Thus one of the characteristic features of circular motion is that the direction of motion of a body changes continuously with time.** Because the speed of the *ball* in its circular path is uniform, the velocity changes uniformly and the ball undergoes uniform acceleration. Thus circular motion is an accelerated motion, even though the speed of the body remains constant. Since this acceleration changes only the direction of the velocity and not its magnitude, the acceleration must always be perpendicular to the velocity. The acceleration is directed toward the centre of the circle. Acceleration directed toward the centre of a circle is called centripetal acceleration. The word centripetal means "*directed toward a centre*".

1.12 RELATION BETWEEN LINEAR AND ANGULAR VELOCITY

To find the speed of a body in circular motion, let us suppose that the ball moves with constant speed v in a circle of radius r (Fig. 1.31). Let the displacement of the ball during the time, t, is the arc PQ of length, *l*. Then its speed, v, will be

$$v = \frac{l}{t}$$

or

$$l = vt \qquad \text{... (1)}$$

If the angle subtended by the arc PQ at the centre O of the circle is θ radians, then by the definition of the angle, we have

$$\theta = \frac{l}{r}$$

or

$$\boxed{l = \theta r} \qquad \text{... (2)}$$

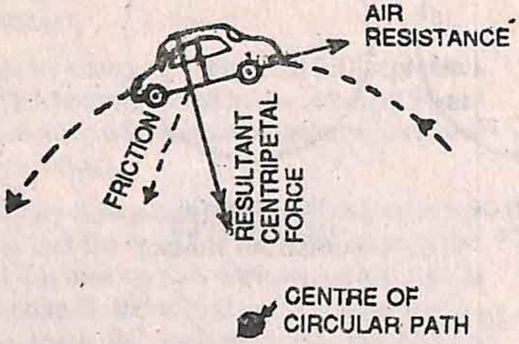


Fig. 1.32 Car negotiating a curve.

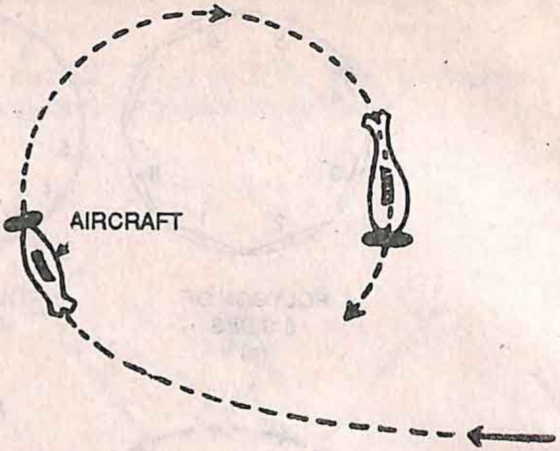


Fig. 1.33 An aircraft looping the loop.

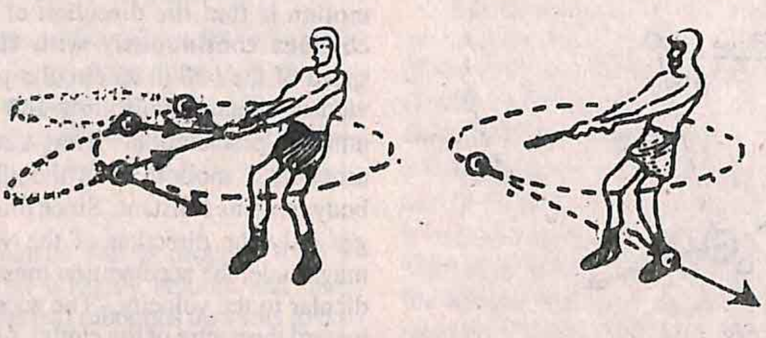


Fig. 1.34 An athlete whirling a hammer in a circle.

From equations (1) and (2), we have

$$\theta r = vt$$

or $$\boxed{\frac{\theta}{t} = \frac{v}{r}} \quad \text{... (3)}$$

In uniform circular motion of a body, the quantity $\frac{\theta}{t}$ is called the angular velocity of the body.

Thus *angular velocity is defined as the angle described by a body per unit time in uniform circular motion.*

It is usually denoted by the Greek letter ω (omega).

$$\text{Thus angular velocity } \omega = \frac{\theta}{t} \quad \text{... (4)}$$

The angle described by the body in one complete revolution in uniform circular motion is 2π radians. If T is the time taken to complete one revolution, then

$$\boxed{\omega = \frac{2\pi}{T}} \quad \text{... (5)}$$

If the particle makes n revolutions in *one second*, the angular velocity

$$\boxed{\omega = 2\pi n} \quad \text{... (6)}$$

The unit of measurement of angular velocity is the radian per second or rad/s or rad s^{-1}.

From equations (3) and (4), we have

$$\boxed{\omega = \frac{v}{r}} \quad \text{.... (7)}$$

or $$\boxed{v = \omega r} \quad \text{... (8)}$$

∴ Speed of the body in circular motion

= angular speed × radius.

It must be noted that if the body has *non-uniform* circular motion *e.g.*, motion of a minute hand in a mechanical clock, then we talk about the *average angular speed* of the body.

1.13 DISTANCE FROM SPEED-TIME GRAPH

We have learnt earlier in this Chapter that the distance travelled by a body moving with a *uniform speed* in a given time interval can be found in the followig *two ways* :

(*i*) Distance travelled = Speed × time taken

(*ii*) Distance travelled = Area under the speed-time graph for the given time interval.

For example, in Fig. 1.18, the area of the rectangle PQSR (shaded) is the distance travelled in that interval.

In the case of *non-uniform motion* (*i.e.*, for objects which do not move with uniform speed), we can no longer use the equation

Distance travelled = Speed × time interval because in this case the speed changes with time. However, in the second equation

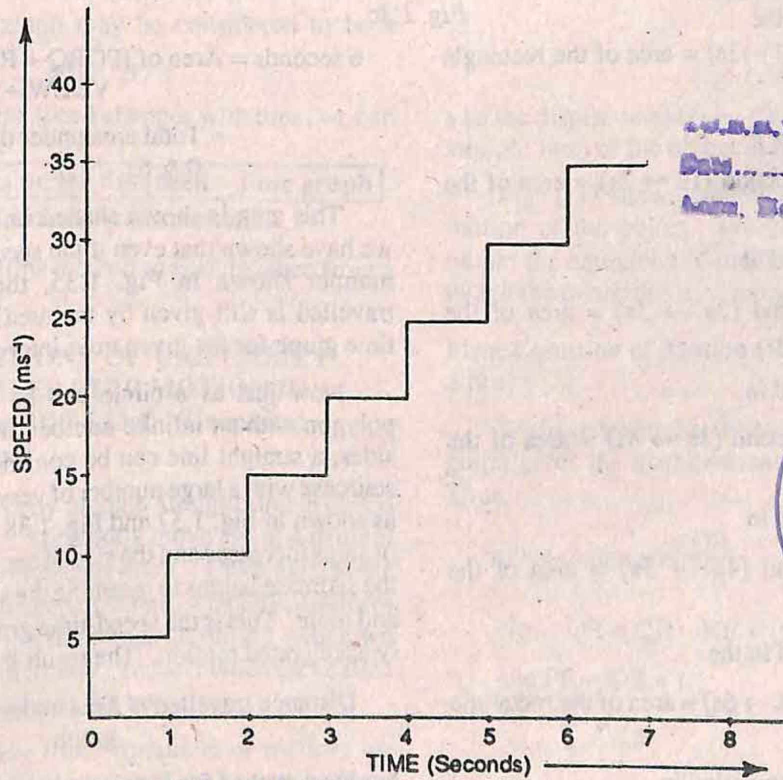
Distance travelled = Area under the speed-time graph for the given time interval

can be used even for objects moving with changing speeds. Let us try to understand why this is so.

We treat the speed-time graph in a manner similar to the way in which we studied an object moving in a circle. There we discovered that a circle is nothing but a polygon with infinite sides. Let us start with a speed-time graph shown in Fig. 1.35. The graph shows that the speed of the object increases in steps. The body starts a time t = o with a speed of 5 ms^{-1} which remains constant upto time t = 1 s when it abruptly increases to 10 ms^{-1}.

The speed remains 10 ms^{-1} upto t = 2 s when it increases by another 5 ms^{-1} and so on. Thus, during the first second, speed is constant at 5 ms^{-1}, during the second second speed is constant at 10 ms^{-1}, during the third second speed is constant at 15 ms^{-1} and so on. Let us find the total distance travelled by the body during the first six seconds. To find this distance we add up the distances covered in each second upto the 6th second.

Referring to Fig. 1.36, we have,



SPEED-TIME GRAPH SHOWING STEP-WISE INCREASE IN SPEED

Fig. 1.35

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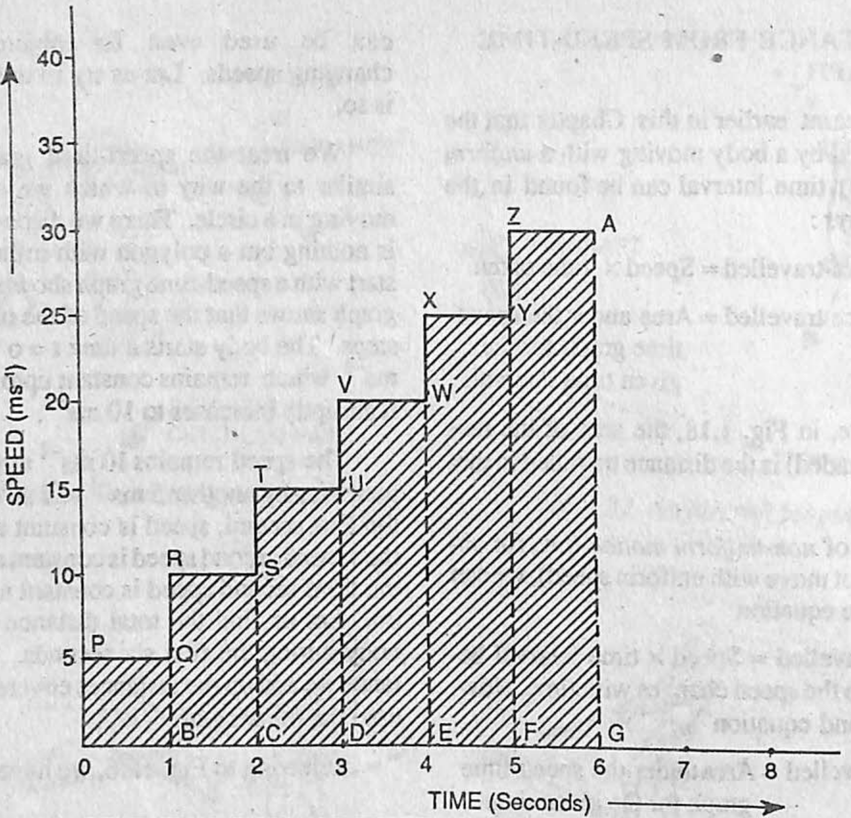


COMPUTING DISTANCE TRAVELLED WITH A SPEED-TIME GRAPH

Fig. 1.36

Distance travelled in the

FIRST second (0 →1s) = area of the rectangle POBQ

Distance travelled in

the SECOND second (1s → 2s) = area of the rectangle RBCS

Distance travelled in

the THIRD second (2s → 3s) = area of the rectangle TCDU

Distance travelled in

the FOURTH second (3s → 4s) = area of the rectangle VDEW

Distance travelled in

the FIFTH second (4s → 5s) = area of the rectangle XEFY

Distance travelled in the

SIXTH second (5s → 6s) = area of the rectangle ZFGA

∴ Total distance travelled in 6 seconds = Area of [POBQ + RBCS + TCDU + VDEW + XEFY + ZFGA]

= Total area under the graph between 0 & 6s.

This area is shown shaded in Fig. 1.36. Thus, we have shown that even if the speed changes in the manner shown in Fig. 1.35, the total distance travelled is still given by the area under the speed time graph for the given time-interval.

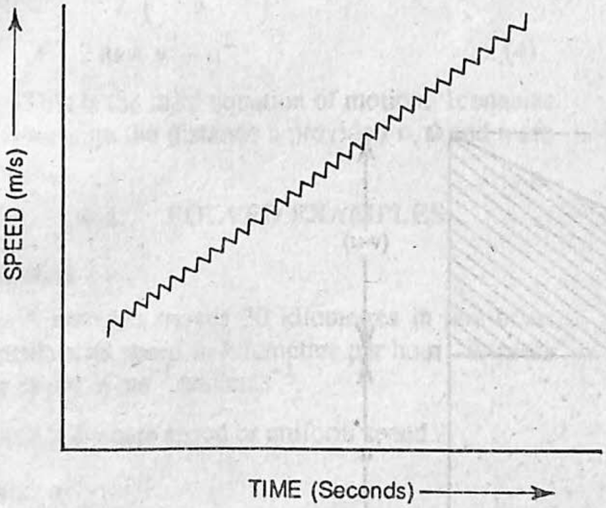
Now just as a circle can be thought of as a polygon with an infinite number of very very small sides, a straight line can be considered to be like a staircase with a large number of very very small steps as shown in Fig. 1.37 and Fig. 1.38. As the number of steps increases and the size of each step decreases, the staircase begins to resemble the straight line more and more. This is the speed-time graph of a uniformly accelerated motion. The result that

Distance travelled = Area under the speed-time graph

has been proved for a staircase speed-time graph. *It* *must hold for a straight line also.* After all, the straight-line is nothing but a staircase with a very large number of steps, each step being of very very small size.

Therefore, even though we cannot use the equation

Distance = Speed × time



[A straight line graph may be considered to be a staircase]

Fig. 1.37

for an object whose speed changes with time, we can still use the result

distance = area under the speed – time graph

for both uniform and non-uniform motion.

We shall use this method to find distance from a speed-time graph.

1.14 EQUATIONS OF UNIFORMLY ACCELERATED MOTION IN A STRAIGHT LINE (Graphical Method)

Motion of a body along a straight line is called *rectilinear motion*. Let a body move along a *straight line* with *a uniform acceleration*. There exist some relations between displacement, velocity, uniform acceleration and the time-interval during which we study the motion of a body. These relations are called ***equations of motion*** of the body.

While deriving these equations of motion, we assume the direction of motion of the body to be fixed and hence we will only consider the magnitudes of the vectors (displacement, velocity and uniform acceleration) involved.

Consider an object moving with a uniform velocity u in a straight line. Let it be given a uniform acceleration a at time t = 0 when its velocity is u which we shall call the initial velocity. As a result of the acceleration, its velocity increases to v in time t. The velocity v will be called the final velocity. Let s be the displacement (*i.e.*, the distance travelled in a straight line) of the object in time t.

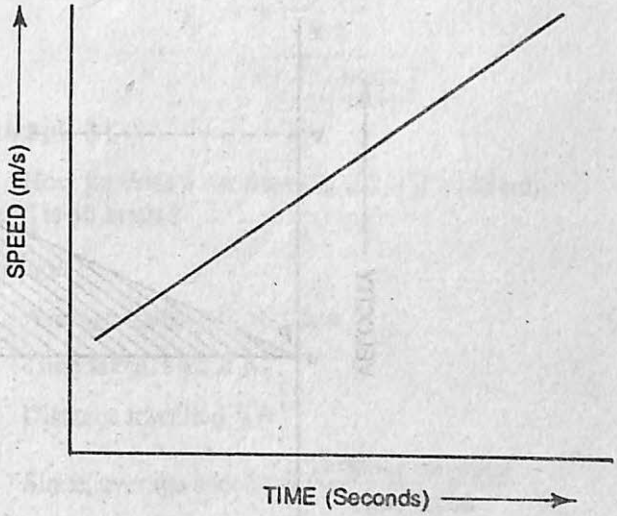


Fig. 1.38

Fig. 1.39 shows the velocity-time graph of the motion of the object. We shall use this graph to obtain the equations of motion *i.e.*, the relations between the quantities u, v, a, s and t.

First Equation of Motion (Relation between u, v, a & t) :

We have learnt that the *slope* of the velocity-time graph gives the *acceleration* of the moving object. Thus,

$$\text{Acceleration } a = \frac{QR}{PR}$$

Now, $QR = QB - RB = (v - u)$

and $PR = OB = t$

$$\therefore\ a = \frac{v-u}{t}$$

or $at = v - u$

distance travelled and the total time taken using $v = \frac{s}{t}$ for each segment of the trip, and then for the totals.

Total distance travelled $= v_1 t_1 + v_2 t_2$

$$= 80.0 \times 1.50 + 50 \times 0.50$$

$$= 145 \text{ km}$$

Since, average speed $= \dfrac{\text{Total distance travelled}}{\text{total time taken}}$

$$= \frac{145 \text{ km}}{(1.50 + 0.50) \text{ h}}$$

$$= \boxed{72.5 \text{ km/h}}$$

Example 5 :

Determine (i) the average speed and (ii) the average velocity of an automobile if it travels a total distance of 165 km in 3.0 h and its final position is 138 km due south of its starting point.

Solution :

(i) Here,

$s = 165$ km

$t = 3.0$ h

average speed $v = ?$

Now, average speed $= v = \dfrac{s}{t} = \dfrac{165 \text{ km}}{3.0 \text{ h}}$

$$= \boxed{55 \text{ km/h}}$$

(ii) Here, displacement $\vec{s} = 138$ km south

time $t = 3.0$ h

average velocity $\vec{v} = ?$

Since, average velocity $\vec{v} = \dfrac{\text{Displacement}}{\text{time}}$

$$= \frac{\vec{s}}{t}$$

$$= \frac{138 \text{ km}}{3.0 \text{ h}} \text{ south}$$

$$= \boxed{46.0 \text{ km/h south}}$$

Example 6 :

A car travels 30 km at a uniform speed of 40 km/h and the next 30 km at a uniform speed of 20 km/h. Find its average speed.

Solution :

We know that

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

$$\text{or time taken} = \frac{\text{distance travelled}}{\text{speed}}$$

$\therefore$ Time taken to travel the first 30 km (t_1)

$$= \frac{30 \text{ km}}{40 \text{ km/h}}$$

$$= 0.75 \text{ h}$$

$\therefore$ Time taken to travel the next 30 km (t_2)

$$= \frac{30 \text{ km}}{20 \text{ km/h}}$$

$$= 1.5 \text{ h}$$

$\therefore$ Total time taken $= t = t_1 + t_2$

$$= 0.75 \text{ h} + 1.5 \text{ h}$$

$$= 2.25 \text{ h}$$

Total distance travelled $= s = s_1 + s_2$

$$= 30 \text{ km} + 30 \text{ km}$$

$$= 60 \text{ km}$$

Hence, average speed

$$= \frac{\text{Total distance travelled (s)}}{\text{Total time taken (t)}}$$

$$= \frac{(s_1 + s_2)}{(t_1 + t_2)} = \frac{60 \text{ km}}{2.25 \text{ h}}$$

$$= \boxed{26.66 \text{ km/h}}$$

Example 7 :

On a 60 km track, a train travels the first 30 km at a uniform speed of 30 km/h. How fast must the train travel the next 30 km so as to average 50 km/h for the entire trip ?

Solution :

Given,

$$\left.\begin{aligned} \text{Distance} &= s_1 = 30 \text{ km} \\ \text{Speed} &= v_1 = 30 \text{ km/h} \end{aligned}\right\} \text{For first segment of the trip}$$

$$\left.\begin{aligned} \text{Distance} &= s_2 = 30 \text{ km} \\ \text{Let speed} &= v_2 \text{ km/h} \end{aligned}\right\} \text{For next segment of the trip}$$

Average speed = 50 km/h for the entire trip. Now, time taken to travel the first 30 km

$$= t_1 = \frac{30\text{ km}}{30\text{ km/h}}$$

$$= 1\text{h}$$

and time taken to travel the next 30 Km = t_2

$$= \frac{30\text{ km}}{v_2\text{ km/h}}$$

$$= \frac{30}{v_2}\text{ h}$$

Since, average speed

$$= \frac{\text{Total distance}}{\text{Total time taken}} = \frac{S_1 + S_2}{t_1 + t_2}$$

$$\therefore\ 50\text{ km/h} = \frac{(30+30)\text{ km}}{1\text{ h} + \frac{30}{v_2}\text{ h}}$$

or $$50 = \frac{60}{1 + \frac{30}{v_2}}$$

or $$50\left(1 + \frac{30}{v_2}\right) = 60$$

or $$\frac{50 \times 30}{v_2} = 10$$

$$\therefore\ v_2 = \frac{50 \times 30}{10}\text{ km/h}$$

$$\boxed{= 150\text{ km/h}}$$

Example 8 :

A train is travelling from a station P to a station S, stops at stations Q and R as shown in the following table. Find the average speed of the train between P and Q, between R and S, and for the whole journey.

Station	Times	Distances from P
P depart	10.00	0 km
Q arrive	11.10	84 km
Q depart	11.15	84 km
R arrive	12.10	170 km
R depart	12.15	170 km
S arrive	13.10	247 km

Solution :

Now, Time taken from P to Q = 1h 10 min

$$= 1\frac{1}{6}\text{ h}$$

Distance from P to Q = 84 km

∴ Average speed from P to Q

$$= \frac{\text{distance from P to Q}}{\text{time taken from P to Q}}$$

$$= \frac{84\text{ km}}{1\frac{1}{6}\text{ h}} = \boxed{72\text{ km h}^{-1}}$$

Again, distance from R to S = 77 km

Time taken from R to S = 55 min = $\frac{55}{60}$ h

∴ Average speed from R to S

$$= \frac{\text{Distance from R to S}}{\text{Time taken from R to S}}$$

$$= \frac{77\text{ km}}{\frac{55}{60}\text{ h}}$$

$$= \boxed{84\text{ km h}^{-1}}$$

Total distance for the whole journey = 247 km

Total time taken for the whole journey = $3\frac{1}{6}$ h

∴ Average speed for the whole journey

$$= \frac{\text{Total distance travelled}}{\text{Total time taken}}$$

$$= \frac{247\text{ km}}{3\frac{1}{6}\text{ h}} = \boxed{78\text{ kmh}^{-1}}$$

Example 9 :

The distances S travelled by a particle at times t are as shown in the following table :

S(m)	0	1	4	9	15	21	27	33
t(s)	0	1	2	3	4	5	6	7

Draw the distance-time graph corresponding to these values and from this graph determine the speed of the particle in the time-interval t = 3s and t = 7s.

Solution :

The distance-time graph corresponding to the values given in the above table is as shown in Fig. 1.40.

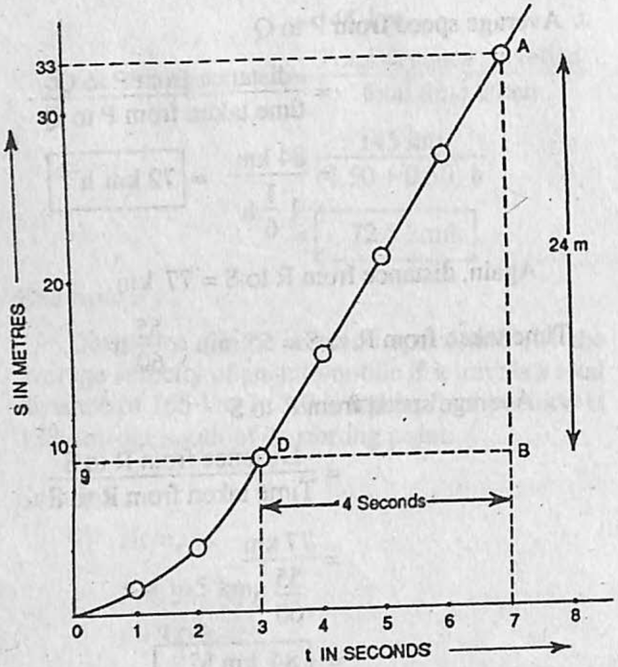


Fig. 1.40

We have learnt that the *slope* of the graph gives the *speed* of the particle.

Now the slope of the graph drawn in Fig. 1.40 in the time interval t = 3 seconds and t = 7 seconds is given by

$$\text{Slope} = \frac{AB}{DB}$$

$$= \frac{24 \text{ metres}}{4 \text{ seconds}}$$

$$= 6 \text{ metre/second}$$

Hence the *speed* of the particle in the time interval t = 3.5 and t = 7 s is 6 m/s.

Example 10 :

A car starts from A and travels 10 km due west, 20 km north-west, and 30 km due north. Find its distance and bearing from A.

How long will it take to return to A direct at an average speed of 50 km/h ?

Solution :

Let us choose a scale so that 1 cm represents 10 km.

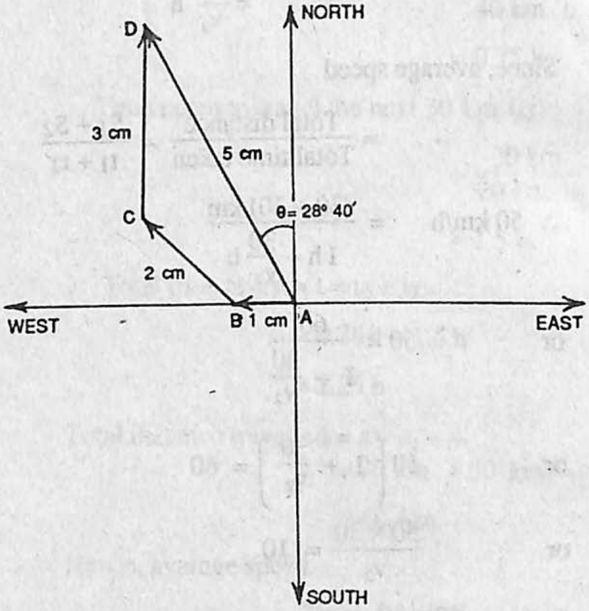


Fig. 1.41

In Fig. 1.41, $\overrightarrow{AB}$ represents the displacement of the car from the point A due west ; $\overrightarrow{BC}$ represents the displacement of the car due north-west (*i.e.*, 45° west of north) and $\overrightarrow{CD}$ represents the displacement of the car due north. A is the starting point of the car and D is the end point. Thus $\overrightarrow{AD}$ represents the resultant displacement of the car from point A. Distance of the car from A is the magnitude of the displacement $\overrightarrow{AD}$.

On measurement, AD = 5 cm

= 50 km

∴ the distance of the car from A to the end point = 50 km

Since the line AD makes an angle $\theta = 28^0 \;\; 40'$

with the north, hence the displacement $\overrightarrow{AD}$ of the car is 50 km, 28° - 40′ west of north.

$$\text{Now speed} = \frac{\text{distance covered}}{\text{time taken}}$$

$$\therefore \text{Time taken} = \frac{\text{distance covered (AD)}}{\text{speed}}$$

$$= \frac{50\text{ km}}{50\text{ km/h}}$$

$$\boxed{= 1\text{ h}}$$

Example 11 :

Fig. 1.42 shows the distance-time graphs of two moving trains P and Q. Which graph has a greater slope ? Which of the two trains is moving faster ?

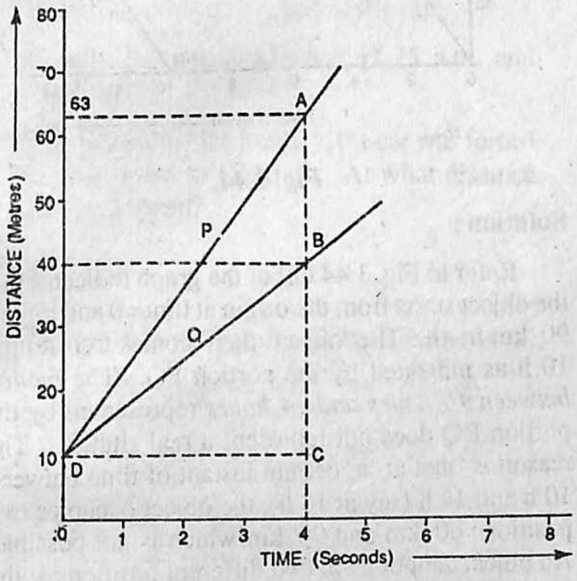


Fig. 1.42

Solution :

Slope of graph of train

$$\text{P} = \frac{\text{AC}}{\text{DC}} = \frac{63\text{ m} - 10\text{ m}}{4\text{ s} - 0\text{ s}}$$

$$= \frac{53\text{ m}}{4\text{ s}} = 13.25\text{ ms}^{-1}$$

$$\text{Slope of graph of train Q} = \frac{\text{BC}}{\text{DC}}$$

$$= \frac{40\text{ m} - 10\text{ m}}{4\text{ s} - 0\text{ s}}$$

$$= \frac{30\text{ m}}{4\text{ s}}$$

$$= 7.5\text{ ms}^{-1}$$

Hence, slope of graph P is greater than that of graph Q.

Since, slope is equal to the speed, the speed of train P is 13.25 m/s while speed of train Q is 7.5 ms^{-1}. Thus the train P is moving faster than the train Q.

Example 12 :

Fig. 1.43 shows the distance-time graph of three tongas A, B and C. On the basis of the graphs, answer the following questions :

(a) Which of the three tongas is travelling the fastest ? Which of the three tongas is travelling the slowest ?

(b) Are all three tongas ever at the same point on the road ?

(c) When tonga A passes tonga C, where is tonga B ?

(d) How far did tonga A travel between the time it possed tongas B and C ?

Solution :

(a) In order to find out which tonga is travelling the fastest and which is travelling the slowest, we calculate the slope of the graph of each tonga as the slope gives the speed of the tonga.

∴ Speed of tonga A = slope of the distance–time graph of tonga A

$$= \frac{\text{DE}}{\text{FE}} = \frac{13\text{ km} - 6\text{ km}}{1.6\text{ h} - 0\text{ h}} = \frac{7\text{ km}}{1.6\text{ h}}$$

$$= 4.37\text{ km/h}$$

Speed of tonga B = Slope of the distance-time graph of tonga B

$$= \frac{\text{GH}}{\text{FH}}$$

$$= \frac{11.6\text{ km} - 6\text{ km}}{1.2\text{ h} - 0\text{h}} = \frac{5.6\text{ km}}{1.2\text{ h}}$$

$$= 4.67\text{ km/h}$$

Slope of tonga C = Slope of the distance–time graph of tonga C

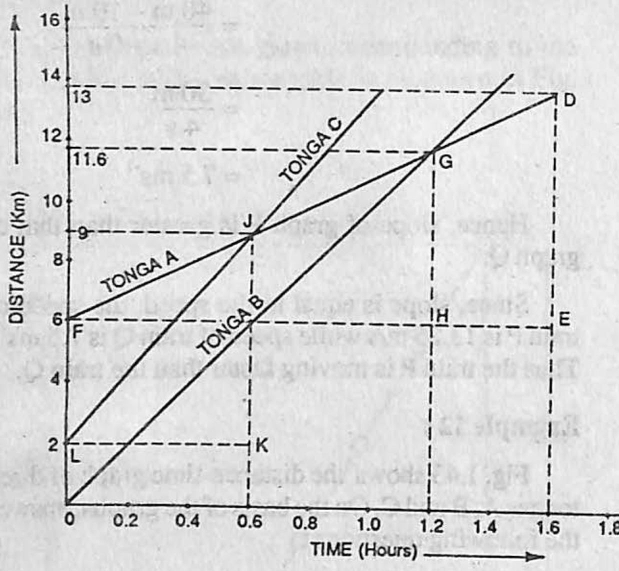


Fig. 1.43

$$= \frac{JK}{LK}$$

$$= \frac{9\text{ km} - 2\text{ km}}{0.6\text{ h} - 0\text{ h}}$$

$$= \frac{7\text{ km}}{0.6\text{ h}}$$

$$= 11.67\text{ km/h}$$

It is clear that *tonga C* having speed 11.67 km/h is the *fastest* and the *tonga A* having speed 4.37 km/h is the *slowest.*

(b) The three tongas are *never* at the same point on the road because all the three graphs do not intersect at any one point [Fig. 1.43].

(c) Tonga A passes tonga C at time = 0.6 h(see Fig. 1.43). We notice from the graph of tonga B that it is 6 km from the origin 0 at time = 0.6 h.

(d) Tonga A passed tonga c at time = 0.6 h and passed tonga B at time = 1.2 h.

Now, the position of tonga A at time 1.2 h = 11.6 km from origin 0. The position of tonga A at time 0.6 h = 6 km from origin 0. Hence between time 0.6 h and 1.2 h, the tonga A travelled a distance = 11.6 km − 6 km

$$\boxed{= 5.6\text{ km}}$$

Example 13 :

Fig. 1.44 is the distance-time graph of an object. Do you think it represents a real situation ? If so, why?

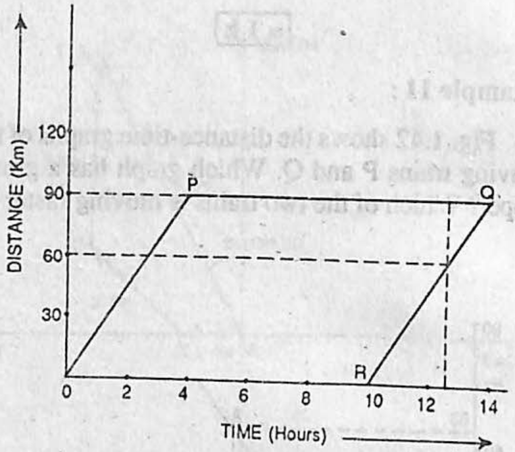


Fig. 1.44

Solution :

Refer to Fig. 1.44 OP of the graph indicates that the object starts from the origin at time=0 and travels 90 km in 4h. The object then comes to rest upto 10 h as indicated by the portion PQ. The *motion between 10 hours and 14 hours* represented by the portion RQ does not represent a real situtiion. The reason is that at a certain instant of time between 10 h and 14 h (say at 13 h), the object occupies two positions 60 km and 90 km which is not possible. An object cannot be at two different positions at the same time. Hence, the graph of Fig. 1.44 does not represent a real position.

Example 14 :

The following is the distance-time table of a moving car :

(a) Draw distance-time graph of the car.

(b) When was the car travelling at the greatest

Time	10.05 a.m.	10.25 a.m.	10.40 a.m.	10.50 a.m.	11.00 a.m.	11.10 a.m.	11.25 a.m.	11.40 a.m.
Distance	0 km	5 km	12 km	22 km	26 km	28 km	38 km	42 km

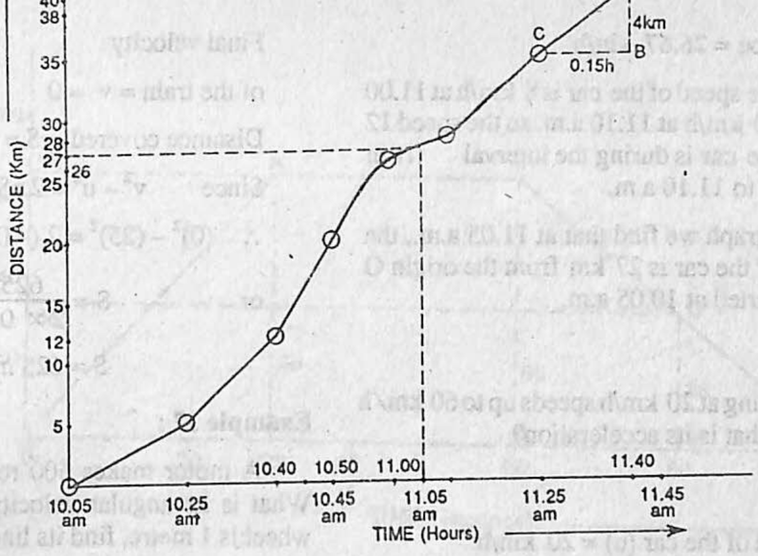


Fig. 1.45

speed ?

(c) What is the average speed of the car?

(d) What is the speed between 11.25 a.m. and 11.40 a.m.?

(e) During a part of the journey, the car was forced to slow down to 12 Km/h. At what distance did this happen?

Solution :

(a)

(b) The speed of the car during the interval 10.05 a.m. to 10.25 a.m. $= \dfrac{\text{distance}}{\text{Time}} = \dfrac{5 \text{ Km}}{0.20 \text{ h}}$

$$= 25 \text{ Km/h}$$

The speed of the car during the interval 10.25 a.m. to 10.40 a.m. $= \dfrac{12 \text{ Km} - 5 \text{ Km}}{0.15 \text{ h}} = \dfrac{7 \text{ Km}}{0.15 \text{ h}}$

$$= 46.67 \text{ Km/h.}$$

The speed of the car during the interval 10.40 a.m. to 10.50 a.m.

$$= \frac{22 \text{ Km} - 12 \text{ Km}}{0.10 \text{ h}} = \frac{10\text{Km}}{0.10\text{h}} = 100 \text{ Km/h}$$

The speed of the Car during the interval 10.55 a.m. to 11.00 am.

$$= \frac{26\text{Km} - 22\text{Km}}{0.50\text{h}} = \frac{4 \text{ Km}}{0.50\text{h}} = 8 \text{ Km/h}$$

The speed of the Car during the interval 11.00 a.m. to 11.10 a.m.

$$= \frac{28\text{Km} - 26\text{Km}}{0.10\text{h}} = \frac{2 \text{ Km}}{0.10\text{h}} = 20 \text{ Km/h}$$

The speed of the car during the interval 11.10 a.m. to 11.25 a.m.

$$= \frac{38\text{Km} - 28\text{Km}}{0.15\text{h}} = \frac{10 \text{ Km}}{0.15\text{h}} = 66.67 \text{ Km/h}$$

The speed of the car during the interval 11.25 a.m. to 11.40 a.m. $= \dfrac{42 \text{ km} - 38 \text{ Km}}{0.15 \text{ h}} = \dfrac{4 \text{ km}}{0.15 \text{ h}}$

$$= 26.67 \text{ Km/h.}$$

Thus it is clear that the greatest speed attained by the car is 100 Km/h during the interval 10.40 a.m. to 10.50 a.m.

(c) Average speed $= \dfrac{\text{Total distance travelled}}{\text{Total time taken}}$

Now, total distance travelled = 5Km + 7Km + 10 Km + 4 Km + 2Km + 10 Km + 4Km = 42 Km

Total time taken = 0.20 h + 0.15h + 0.10h + 0.50h + 0.10h + 0.15h + 0.15h = 1.35h

$$\therefore \text{Average speed} = \frac{42\text{Km}}{1.35 \text{ h}} = \boxed{31.3 \text{ Km/h}}$$

(d) Slope of the graph between 11.25 a.m. and 11.40 a.m. $= \dfrac{AB}{CB}$

$$= \frac{4 \text{ Km}}{0.15 \text{ h}}$$

$$\boxed{= 26.67 \text{ Km/h}}$$

∴ Speed of the Car between 11.25 a.m. and

11.40 a.m. = Slope = 26.67 km/h

(e) Since the speed of the car is 8 km/h at 11.00 a.m. and 20 km/h at 11.10 a.m. so the speed 12 km/h of the car is during the interval from 11.00 a.m. to 11.10 a.m.

From the graph we find that at 11.05 a.m., the distance of the car is 27 km from the origin O when it started at 10.05 a.m.

Example 15 :

A car travelling at 20 km/h speeds up to 60 km/h in 6 seconds. What is its acceleration?

Solution :

Initial speed of the car (u) = 20 km/h

Final speed of the car = v = 60 km/h

Time taken = t = 6 seconds

$$= \frac{6}{60\times 60} = \frac{1}{600}\ \text{h}$$

Acceleration = a = ?

$$\text{Now, } a = \frac{v-u}{t} = \frac{(60-20)\,\text{Km/h}}{\frac{1}{600}\ \text{h}}$$

$$= \mathbf{24000\ km/h^2}$$

$$= \mathbf{1.85\ m/s^2}$$

Example 16 :

A train is travelling at a speed of 90 kmh^{-1}. The brakes are applied so as to produce a uniform acceleration of $-0.5\ \text{m/s}^2$. Find how far the train goes before it stops.

Solution :

We are given,

Initial velocity of the train

$$= u = 90\ \text{km/h}$$

$$= \frac{90\times 1000}{3600}$$

$$= 25\ \text{ms}^{-1}$$

Retardation (negative acceleration)

$$= a = -0.5\ \text{m/s}^2$$

Final velocity of the train = v = 0

Distance covered = S = ?

Since $v^2 - u^2 = 2\,aS$

$$\therefore\ (0)^2 - (25)^2 = 2\,(-0.5)\times S$$

$$\text{or}\quad S = \frac{625}{2\times 0.5}\ \text{m}$$

$$S = 625\ \text{m}.$$

Example 17 :

A motor makes 500 revolutions in 5 minutes. What is its angular velocity ? If the radius of the wheel is 1 metre, find its linear velocity.

Solution :

Here, the angle described by the motor in 5 minutes

$$= 500\times 2\pi = 1000\ \pi\ \text{rad}$$

$$\text{Angular velocity} = \omega = \frac{1000\ \pi}{5\times 60}$$

$$= \frac{10\ \pi}{3}\ \textbf{rad/s}$$

and linear velocity = v = r ω

$$= 1\times\frac{10\ \pi}{3}$$

$$= 1\times\frac{10}{3}\times\frac{22}{7}$$

$$\boxed{= \mathbf{10.47\ m/s}}$$

Exmaple 18 :

The speed-time graph of the motion of a car is shown in Fig. 1.46. Find the accelerations of the car during the given interval. Also find the average speed throughout the interval.

Solution :

Since OA is a straight line, the acceleration of the car in the first 30 s is uniform and of magnitude $\frac{66}{30}\ \text{ms}^{-2}$ *i.e,* the slope $\frac{AN}{ON}$.

For the next 30 s the speed is 66 ms^{-1} throughout and the acceleration is, therefore, zero.

From the instant t = 60 s to the instant t = 80 s the

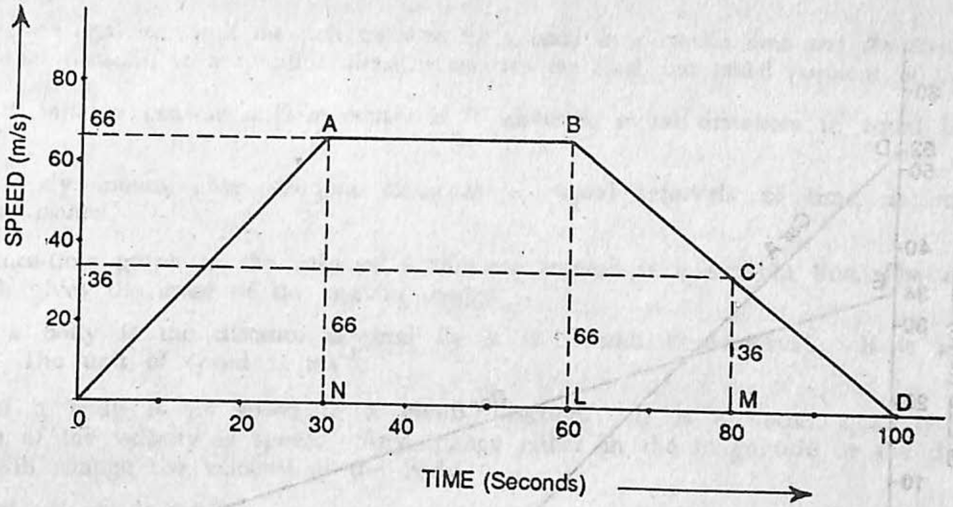


Fig. 1.46

speed falls from 66 to 36 ms^{-1} and the acceleration is uniform and of magnitude $\frac{(36-66)\ m/s}{20\ s} = -1.5$ ms^{-2}.

For the last 20s the acceleration is again uniform but of magnitude $-\frac{36}{20}\ ms^{-2}$, *i.e.*, the slope $\frac{CM}{MD}$.

The total distance travelled is represented by the *area* under the speed-time curve, and hence equals to area of triangle OAN + area of rectangle NABL + area of the trapezium BLMC + area of triangle CMD

$$= \frac{1}{2} \times 30 \times 66 + 30 \times 66 + \frac{1}{2} \times 20 \times (66+36) + \frac{1}{2} \times 36 \times 20$$

$$= 4350\ m$$

∴ Average speed throughout the interval

$$= \frac{\text{Total distance travelled}}{\text{Total time taken}}$$

$$= \frac{4350\ m}{100\ s}$$

$$\boxed{= 43.5\ ms^{-1}}$$

Example 19 :

A driver of a car travelling at 52 km/h applies the brakes and decelerates uniformly. The car stops in 5 seconds. Another driver going at 34 km/h applies his brakes slower and stops after 10 seconds. On the same graph paper, plot the speed versus time graph for two cars. Which of the two cars travelled farther after the brakes were applied ?

Solution :

Fig. 1.47 shows the speed-time graph of two cars A and B.

Distance travelled by car A before stopping (s_1)

$$= \text{area of triangle DOF}$$

$$= \frac{1}{2} \times \text{base} \times \text{height}$$

$$= \frac{1}{2} \times OF \times OD$$

$$= \frac{1}{2} \times 5\ s \times \frac{130}{9}\ ms^{-1}\ (\text{as } 52\ km/h = \frac{52000\ m}{3600\ s} = \frac{130}{9}\ ms^{-1})$$

$$= 36.1\ m$$

Similarly, distance travelled by car B before stopping (S_2)

$$= \text{area of traingle EOG}$$

$$= \frac{1}{2} \times OG \times OE$$

$$= \frac{1}{2} \times 10\ s \times \frac{85}{9}\ ms^{-1}\ (\text{as } 34\ km/h = \frac{34000\ m}{3600\ s})$$

$$= 47.2\ m$$

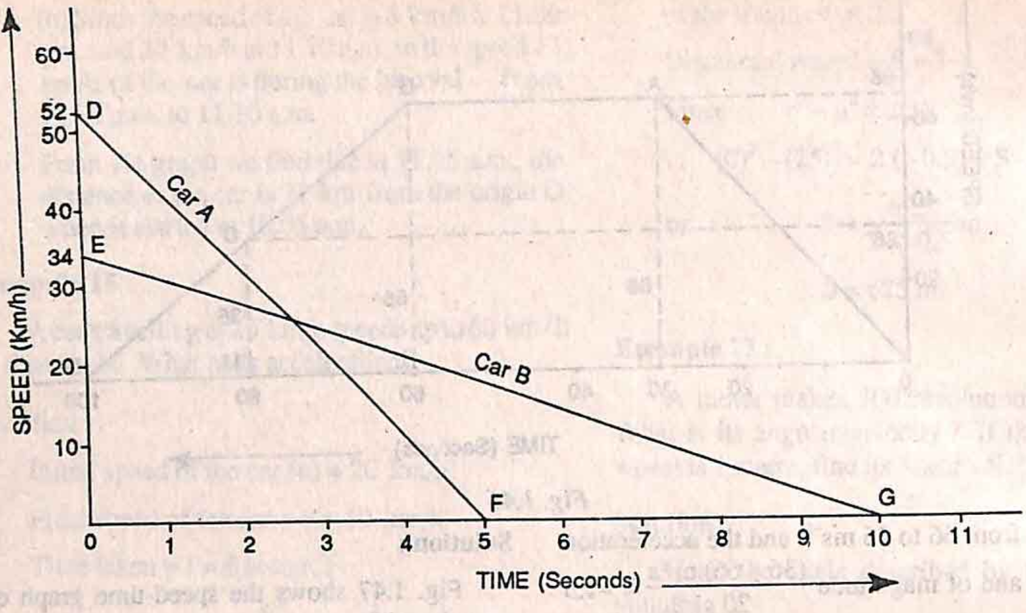


Fig. 1.47

Hence car B travelled farther after the brakes were applied.

Example 20 :

(i) What is the final speed of an object, and (ii) how far does it travel while accelerating if its initial speed is 10.0 m/s and it accelerates at 8.0 m/s^2 for 5.00 seconds ?

Solution :

Given,

Initial speed = $u = 10\ \text{ms}^{-1}$

Acceleration = $a = 8.0\ \text{ms}^{-2}$

Time = $t = 5.00$ s

Final Velocity = v = ?

Distance covered = S = ?

(i) By using the equation of motion,

$$v = u + at$$

We have,

$$v = 10\ \text{ms}^{-1} + (8.0\ \text{m/s}^2)\ (5.00\ \text{s})$$

$$\boxed{= 50\ \text{ms}^{-1}}$$

(ii) By using the equation of motion

$$S = ut + \frac{1}{2}at^2$$

We have,

$$S = (10\ \text{ms}^{-1})\ (5.00\ \text{s}) + \frac{1}{2}\ (8.00\ \text{m/s}^2)\ (5.00\ \text{s})^2$$

$$\boxed{= 150\ \text{m}}$$

SUMMARY

1. The continuous change of position of a body with respect to another is called *motion*. Rest and motion are relative. The change in the position of a body in a particular specified direction is called its *displacement*.

Distance is the total length of the path travelled by a body in a certain time and the displacement is the shortest distance, in a specified direction between the final and initial positions of the body.

2. A body is said to possess *uniform motion* if it traverses equal distances in equal intervals of time.

3. When a body moves over unequal distances in equal intervals of time, it possesses *non-uniform motion.*

4. The distance-time graph in the case of a uniform motion is a straight line. The *slope* of this graph gives the *speed* of the moving body.

5. *Speed* of a body is the distance covered by it in a unit time-interval. It is a *scalar* quantity. The unit of speed is ms^{-1}.

6. *Velocity* of a body is its speed in a given direction. It is a vector quantity. The magnitude of the velocity is speed. Any change either in the magnitude or the direction or both will change the velocity of the body.

   The unit of velocity is m/s.

7. *Average speed* of a body between two points is measured by the total distance covered by the body between those points divided by the total time taken by the body to travel that distance.

8. The velocity of a body at a given instant of time is known as its *instantaneous velocity.*

9. When a body traverses equal distances in equal intervals of time, however small these intervals may be, and it *continues to move in the same direction,* the body is said to possess *uniform velocity.*

10. A body is said to move with *variable velocity* if it traverses equal distances in unequal intervals of time, direction remaining same or not.

11. Vector quantities are those physical quantities which have magnitude as well as direction whereas scalar quantities have magnitude only.

12. *Acceleration* is the rate of change of velocity of a body. It is a vector quantity. The unit of acceleration is m/s^2.

    Negative acceleration is called retardation or deceleration.

13. Motion of a body along a straight line is called *rectilinear* motion.

14. Equations of motion of a body are:

    (*i*) $v = u + at$

    (*ii*) $s = ut + \frac{1}{2}at^2$ or $s = ut$ if $a = 0$ (for uniform motion)

    (*iii*) $2as = v^2 - u^2$

    where u = initial velocity of a body
    v = final velocity of a body
    a = uniform acceleration
    t = time taken
    s = distance covered.

15. If the velocity of a body changes equally in equal intervals of time, however small these intervals may be, the body is said to possess *uniform acceleration* or *uniformly accelerated motion.*

The velocity-time graph for uniformly accelerated motion is a straight line whose *slope* gives the *acceleration*.

16. A body is said to move with *non-uniformly accelerated motion* if its change in velocity in successive equal intervals of time may not be the same.

The velocity-time graph for such a motion may have any shape (other than a straight line).

The *distance* travelled is equal to the *area* under the velocity-time graph.

17. If a body moves with a uniform speed in a circular path, its motion is called *uniform circular motion*.

18. One of the characteristic features of circular motion is that the direction of motion of a body changes continuously with time.

19. Circular motion is an *accelerated motion*, even though the speed of the body remains constant.

20. Angular velocity of a body is defined as the angle described by it per unit time in uniform circular motion. It is usually denoted by the Greek letter ω (omega).

$$\omega = \frac{\theta}{t} = \frac{2\pi}{T} = 2\pi n$$

Its unit is rad/s.

21. $v = \omega r$

i.e., Linear speed = angular speed × radius.

QUESTIONS

[A] Objective Type Questions

1. In the case of rectilinear uniform motion, distance-time graph is

(a) a parabola (b) a straight line

(c) a hyperbola (d) a curved line

2. An object moves with a constant velocity of 9.8 ms^{-1}, its acceleration, in ms^{-2} is,

(a) zero (b) 4.9

(c) 9.8 (d) 32

3. An object moves with a constant acceleration of 15 cms^{-2}. If it starts from rest, its speed at the end of the 4th second in cms^{-1}, is

(a) zero (b) 15

(c) 60 (d) 39.2

4. The distance travelled by the object in Q. 3 during the first four seconds, in cm, is

(a) 15 (b) 60

(c) 120 (d) 240

5. During the third second, the acceleration of the object in Q. 3, in cm s^{-2}, is

(a) 5 (b) 10

(c) 15 (d) 20

6. A stone is dropped from a bridge which is 490 m above water. The time required for the stone to reach the water is, in seconds (Take downward acceleration as 9.8 ms^{-2})

(a) 10 (b) 8

(c) 6 (d) 4

7. A coin is tossed upward with a vertical velocity of 49 ms^{-1}. The time required for it to reach its greatest height in seconds, is (Take upward acceleration as -9.8 ms^{-2})

(a) 3 (b) 5

(c) 10 (d) 15

8. The maximum height reached by the coin in Q. 6 is, in metres, approx. (Take upward acceleration as—9.8 ms^{-2})

(a) 50 (b) 100

(c) 120 (d) 240

9. A speed of 90 km/h, expressed in cms^{-1}, is

(a) 2.5 (b) 2500

(c) 3050 (d) 300

Graphs of Velocity Vs. Time for Question 10-15

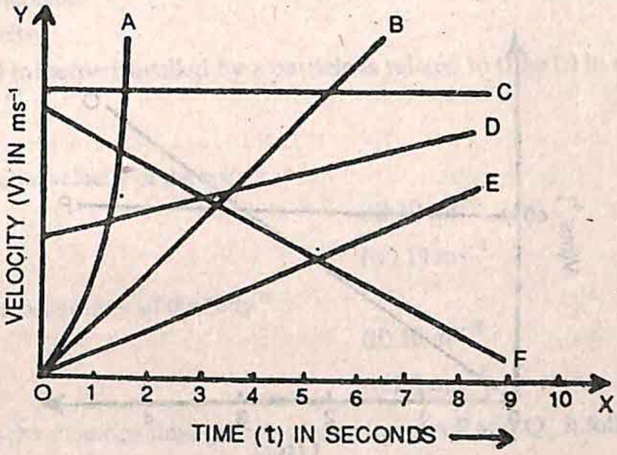


Fig. 1.48

10. For the object in Q. 2, the graph which best shows how its speed changes with time is

(a) A (b) B

(c) C (d) E

11. For the object in Q. (3), the graph which best shows how its speed changes with time is

(a) A (b) B

(c) C (d) D

12. Of the following graphs, the one which represents motion with the greatest acceleration is

(a) B (b) C

(c) D (d) E

13. The graph which represents motion with the greatest speed at t=1 second is

(a) A (b) B

(c) C (d) D

14. The graph which best represents decelerated motion is

(a) C
(b) D
(c) E
(d) F

15. Of the following, the graph which best represents the motion of a stone dropped from a bridge is

(a) A
(b) B
(c) C
(d) D

16. A car travels a distance of 400 km in 6 hours. Its average speed for the trip, in km/h, is, approx;

(a) 67
(b) 35
(c) 140
(d) 2400

17. The distance travelled in 3 seconds by the object represented by graph P in Fig. 1.49 is, approx.

(a) 40 m
(b) 120 m
(c) 60 m
(d) 160 m

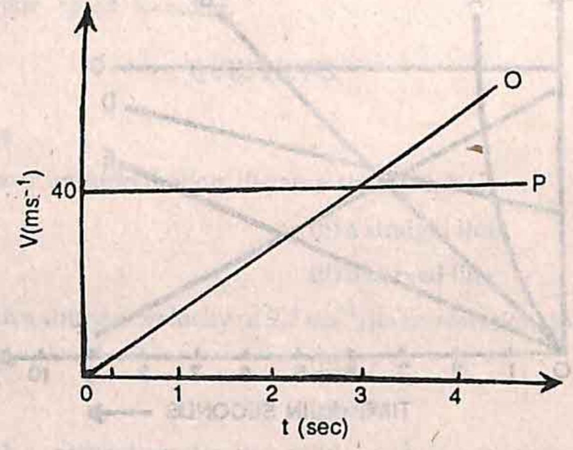


Fig. 1.49

18. The distance travelled in 3 seconds by the object represented by graph Q is, approx.

(a) 40 m
(b) 60 m
(c) 80 m
(d) 120 m

19. Angular velocity of a body is

(a) rate of change of its position
(b) rate of change of its velocity
(c) the angle traced out by it in one second
(d) the rate of change of its acceleration

20. A body moving with uniform circular motion has

(a) no acceleration at all
(b) acceleration which is directed towards the centre of the circular path
(c) acceleration which is directed away from the centre of the circular path
(d) variable acceleration
(e) variable speed with no resultant acceleration acting on it

21. A car increases its velocity from 30 ms^{-1} to 40 ms^{-1} in 1 second. It has changed its velocity by 10 ms^{-1} in 1 s. Therefore, acceleration = ...

22. Choose the right answers in the following :

(a) When a graph of one quantity versus another results in a straight line, the quantities are

(i) both constant

(ii) equal

(iii) directly proportional

(iv) inversely proportional.

(b) A body whose speed is constant

(i) must be accelerated

(ii) might be accelerated

(iii) has a constant velocity

(iv) cannot be accelerated.

(c) When the distance an object travels is directly proportional to the length of time, it is said to travel with

(i) zero velocity

(ii) constant speed

(iii) constant acceleration

(iv) uniform velocity.

23. The distance (S) in metres travelled by a particle is related to time (t) in seconds by the equation of motion

$S = 10t + 4t^2$

(a) What is the initial velocity of the body ?

(i) 4 ms^{-1} (ii) 10 ms^{-1}

(iii) 6 ms^{-1} (iv) 14 ms^{-1}

(b) What is the acceleration of the body ?

(i) 4 ms^{-2} (ii) 10 ms^{-2}

(iii) 2.5 m s^{-2} (iv) 6 m s^{-2}

24. Fig. 1.50 shows the distance-time graphs of two tractors P and Q. It follows from the graphs that

(i) the speed of tractor P is more than that of tractor Q.

(ii) the speed of tractor Q is more than that of tractor P.

(iii) the speed of tractor Q is equal to that of tractor P.

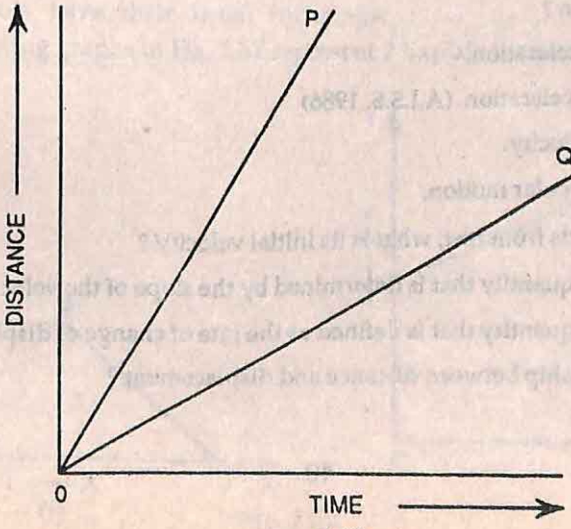


Fig. 1.50

(iv) both the tractors Pand Q have the same speed.

25. Fig. 1.51 shows the velocity-time graph of a cyclist. I follows from the graph that the cyclist

(a) moves with a constant velocity

(c) has an initial velocity and a non-uniform acceleration

(b) starts from rest and has a uniform acceleration

(d) has an initial velocity and its motion is uniformly retarded until it comes to rest.

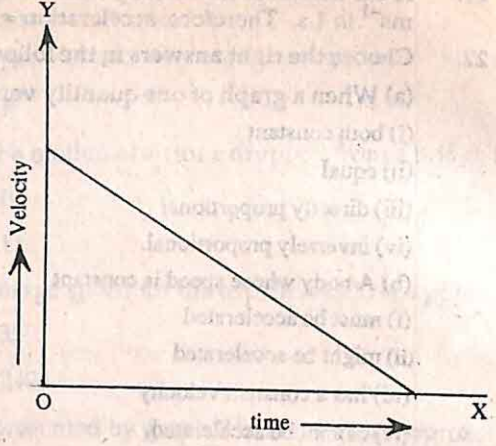


Fig. 1.51.

26. A train, starting from rest, is given a constant acceleration for 40 seconds. It travels a distance S_1 in the first 20 seconds and a distance S_2 in the remaining 20 seconds. Choose the right answer of the following.

(a) $S_1 = S_2$ (b) $S_1 = 4S_2$ (c) $S_2 = 3S_1$ (d) $S_1 = 3S_2$ (e) $S_2 = 2S_1$

27. State a commonly encountered motion whose average velocity is $\frac{u+v}{2}$ where u is the initial velocity and v is the final velocity.

[B] Very Short Answer Type Questions

1. Define : uniform motion.
2. Define: non-uniform motion.
3. What is the unit of acceleration?
4. Give an example of a body moving with a uniformly accelerated motion.
5. Is speed a vector quantity ?
6. Define : speed.
7. What is the unit of speed ?
8. Define : velocity.
9. Give the unit of velocity.
10. Define : angular velocity.
11. Give the unit of angular velocity.
12. In the distance-time graph of uniform rectilinear motion of a body, what does the slope of the curve give ?
13. Define : average speed.
14. Define : displacement. Is it a vector quantity ?
15. What is deceleration ?
16. Give the unit of deceleration.
17. Define : uniform acceleration. (A.I.S.S. 1986)
18. Define : uniform velocity.
19. Define : uniform circular motion.
20. When an object starts from rest, what is its initial velocity ?
21. Name the physical quantity that is determined by the slope of the velocity-time graph.
22. Name the physical quantity that is defined as the rate of change of displacement.
23. What is the relationship between distance and displacement ?

24. Name three vector quantities.

25. Name three scalar quantities.

26. Write the equation of motion connecting s, u, v and a where the symbols have their usual meanings.

[C] Short Answer Type and Essay Type Questions

1. How does the method for getting the resultant of two velocities compare with the method for getting the resultant of two displacements ? **[Hints : Both are vectors]**

2. The formula

distance = speed x time

is correct for two kinds of speed. What are they ?

3. Why does the definition of acceleration apply to declerated motion ?

4. For what type of motion is each of these two formulae correct :

$S = vt \; ; \; S = \frac{1}{2} vt$

5. For motion with constant acceleration, what is the graph of acceleration vs. time ?

6. On a plot of velocity against time, what does the slop of the graph convey us ?

7. When dealing with deceleration motion, what do the letters stand for, if we use the formula :

$v_1 = at$?

8. When an object is projected vertically upwards having acceleration directed towards the ground.

(a) What is the speed at the highest point ?

(b) How does the initial speed at the bottom compare with the object's speed when it comes down again to the same point ?

9. (a) Give one example of each of the following :

speed ; uniform speed ; velocity ; uniform velocity ; acceleration ; deceleration (Retardation) ; uniform acceleration.

(b) When do we say that a body is in uniform acceleration ? (A.I.S.S. 1981)

10. What are equations of motion of a body ? Derive graphically or otherwise the following relations for the uniform rectilinear motion of the body :

(i) $S = ut$

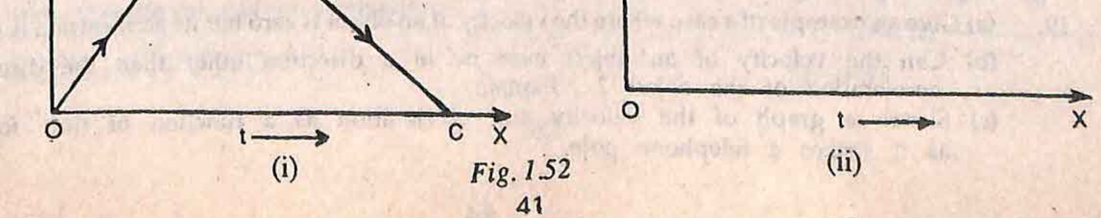
(ii) $S = ut + \frac{1}{2} at^2$ (A.I.S.S. 1986)

(iii) $v = u + at$

(iv) $2aS = v^2 - u^2$

where the symbols have their usual meanings.

11. What do the following graphs in Fig. 1.52 represent ? Explain the nature of motion of the body in each case.



(i) (ii)

Fig. 1.52

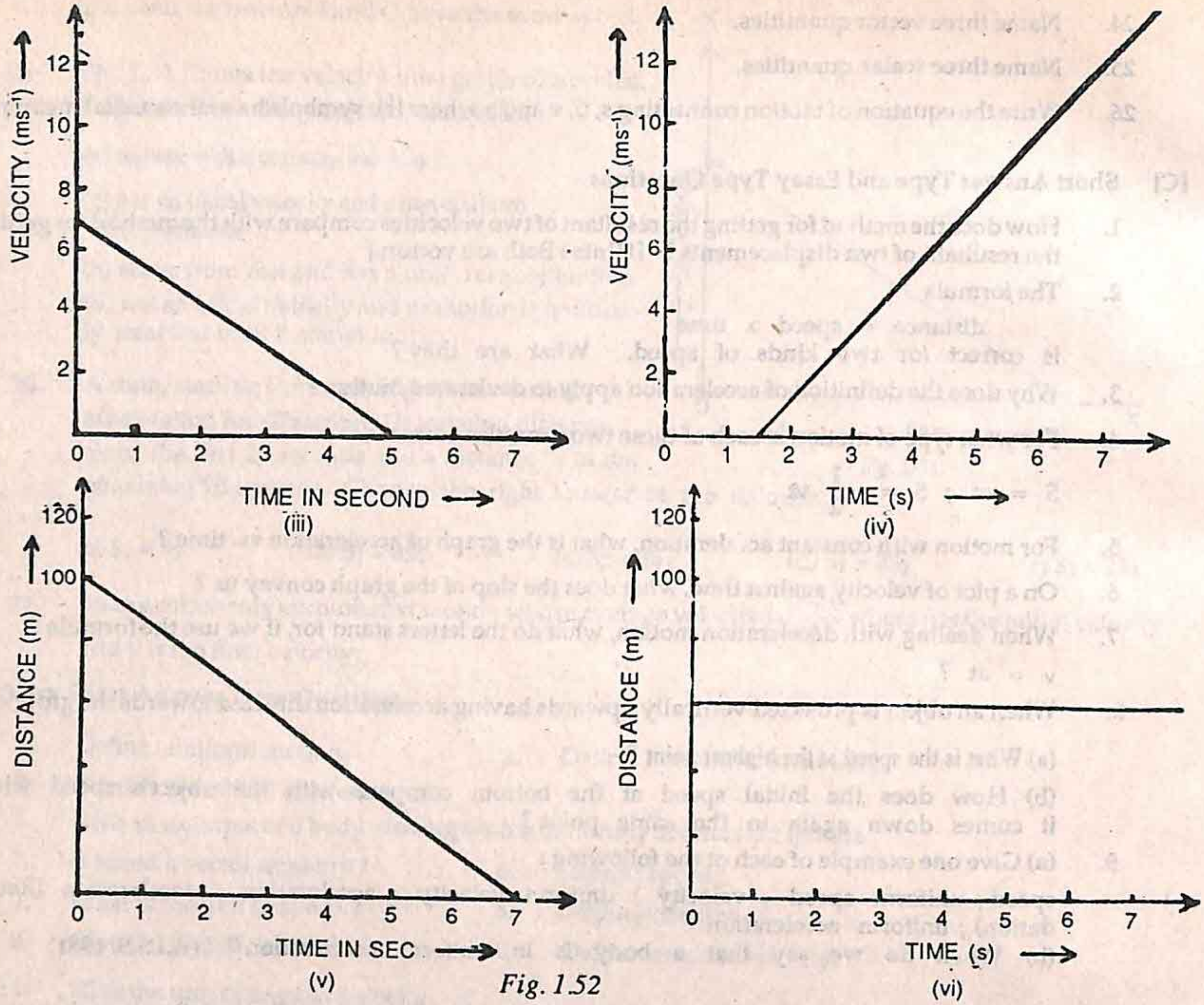


Fig. 1.52

12. Distinguish between uniformly accelerated motion and non-uniformly accelerated motion. Given an example in each case.
What is the nature of graph between velocity and time for (i) uniformly accelerated motion and (ii) non-uniformly accelerated motion ?

13. What is the nature of graph between displacement and time for (i) uniform rectilinear motion and (ii) non-uniform rectilinear motion ?

14. What do you infer, if the distance-time graph is a straight line ?

15. What is angular velocity ? How are the linear velocity and angular velocity related to each other ? (A.I.S.S. 1986)

16. Define : uniform circular motion. Give three examples of this type of motion from daily life situations.
How does uniform circular motion differ from uniform linear motion ?

17. (a) What remains constant for a particle having uniform circular motion–speed or velocity ?
(b) Give an example where a body has constant speed but variable velocity.

18. " Circular motion is an accelerated motion, even though the speed of the body remains constant", Explain.

19. (a) Give an example of a case where the velocity of an object is zero but its acceleration is not zero.
(b) Can the velocity of an object ever be in a direction other than the direction of acceleration of the object ? Explain.
(c) Sketch a graph of the velocity and acceleration as a function of time for a car as it strikes a telephone pole.

20. When a boy throws a ball straight up and catches it again as it comes down, its average velocity during the trip is zero. Why ? Is the average speed zero also ?

21. Consider a small rocket which is shot straight upwards. Assume it to start from rest and accelerate uniformly until its fuel is exhausted. Sketch a graph of the velocity and acceleration as a function of time for the rocket as it rises and then falls to the earth.

22. Distinguish between rest and motion giving an example in each case.

23. Give five examples of bodies in non-uniform motion.

24. Plot speed-time graph of bodies moving with uniform speeds of 4 m/s and 7 m/s. Compare the graphs.

25. Plot distance-time graph of bodies moving with uniform speeds of 4 m/s and 7 m/s. Compare the graphs.

26. The positions of a ball, rolling down an inclined plane, at the end of each second are given in the following table :

Time in seconds	0	1	2	3	4	5
Position in centimetre	0	10	40	90	100	250

Plot a distance-time graph for the motion of the ball. Indicate whether the motion is uniform or non-uniform.

27. A ball is thrown vertically upwards with a velocity u. After ascending a height 'h', it comes back to the thrower. Prove that

(i) Maximum height attained is $\frac{u^2}{2g}$ where g is the acceleration due to gravity.

(ii) Time of ascent is $\frac{u}{g}$. (iii) Time of descent is $\frac{u}{g}$.

(iv) Total time of flight is $\frac{2u}{g}$. (v) Velocity of return is (–u).

(vi) the distance covered is $\frac{u^2}{g}$. (vii) Displacement of the ball is zero.

28. What conclusion can you draw about the velocity of a body from the displacement graph shown in Fig. 1.53.

29. Draw the speed-time graph of a point describing a straight line with *uniform acceleration,* and deduce the formula $v^2 = u^2 + 2as$ where u is the initial velocity, V is the final velocity, a is the uniform acceleration and S is the distance covered in time t seconds.

30. A train starts from a station A to reach another station B, at a distance S from A ; the motion is at first uniformly accelerated for a given time t_1; the velocity then remains constant for a give time t_2; and is then uniformly retarded for a time t_3. Represent the motion in a diagram, and by means of the diagram show that the value of the acceleration is $\frac{2S}{t_1\,[t_1 + t_3 + 2t_2]}$

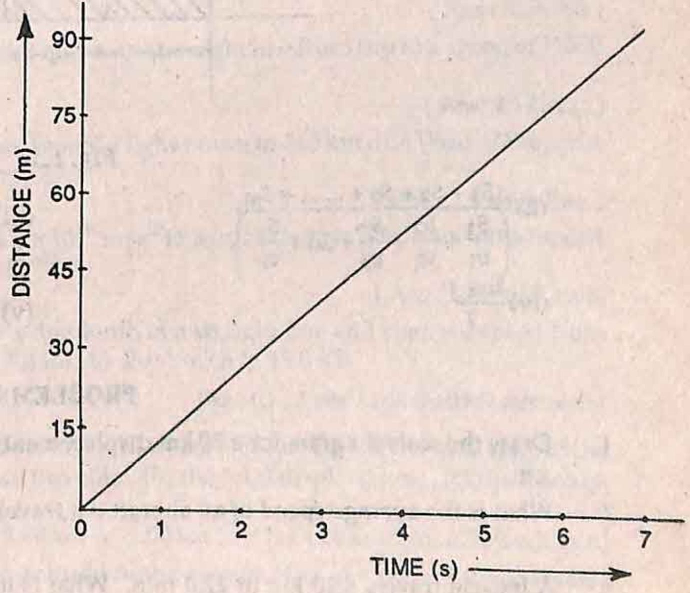


Fig. 1.53

and the value of the retardation is $\frac{2S}{t_3\,[t_1 + t_3 + 2t_2]}$.

31. A body is moving with uniform velocity v. For its motion, state the following :
   (i) S in terms of v and t
   (ii) v in terms of S and t
   (iii) t in terms of v and S
   (iv) value of its acceleration
   (v) its average velocity in total time t
   (vi) its instantaneous velocity at time t
   (vii) nature of graph of v against t, area under this graph.
   (viii) nature of graph of S against t, slope of this graph.

32. A body travels from A to B at a uniform speed u and returns to A with uniform speed v. Show that the average speed of the entire journey is not the arithmetic mean $\frac{u+v}{2}$ but it is $\frac{2uv}{u+v}$.

33. Find the average velocities for the following motions :
   (i) distance S_1 covered at uniform speed v_1 and further distance S_2 at uniform speed v_2. (Also show the nature of v-t graph).
   (ii) various distances $S_1, S_2, S_3, \ldots\ldots\ldots S_n$ covered at uniform velocities $v_1, v_2, v_3, \ldots\ldots v_n$.
   (iii) various distances $S_1, S_2, S_3, \ldots\ldots\ldots S_n$ covered at uniform velocities in periods $t_1, t_2, t_3, \ldots\ldots t_n$.
   (iv) motion at uniform velocity u for half the time and another uniform velocity v for the other half.
   (v) motion at uniform velocity v_1 for time t_1, v_2 for t_2, v_3 for $t_3, \ldots\ldots\ldots\ldots v_n$ for t_n.

[Hints: (i) $\frac{(S_1 + S_2)}{\left(\frac{S_1}{v_1} + \frac{S_2}{v_2}\right)}$

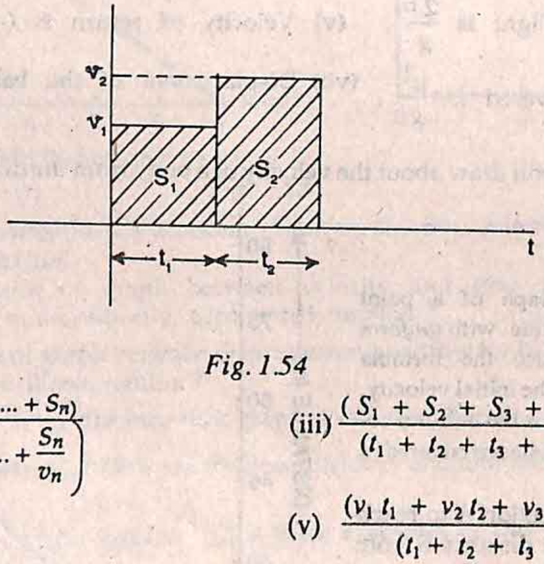


Fig. 1.54

(ii) $\frac{(S_1 + S_2 + S_3 + \ldots\ldots + S_n)}{\left(\frac{S_1}{v_1} + \frac{S_2}{v_2} + \frac{S_3}{v_3} + \ldots + \frac{S_n}{v_n}\right)}$ (iii) $\frac{(S_1 + S_2 + S_3 + \ldots\ldots\ldots + S_n)}{(t_1 + t_2 + t_3 + \ldots\ldots\ldots + t_n)}$

(iv) $\frac{u+v}{2}$. (v) $\frac{(v_1 t_1 + v_2 t_2 + v_3 t_3 + \ldots\ldots + v_n t_n)}{(t_1 + t_2 + t_3 + \ldots\ldots + t_n)}$]

PROBLEMS

1. Draw the scale diagram for a 30 km displacement that is 35° south of east using a scale of 1 cm = 10 km.

2. What is the average speed of an aircraft if it travels 520 km in 55 min ?

[Ans : 567 km/h]

3. A bicycle travels 8.20 km in 22.0 min. What is its average speed (a) in metres per second, (b) in kilometres per hour ?

[Ans. (a) 6.21 m/s; (b) 22.4 km/h]

4. How far does a car travel in 2.5 h if its average speed is 56 km/h ?

[Ans : 140 km]

5. Draw the scale diagrams of the following displacement vectors using a scale of 1 cm = 20 km :

(a) 50 km due west
(b) 80 km 25° south of west
(c) 130 km 35° east of north
(d) 35 km 22° west of south
(e) 79 km 48° north of east.

6. The star Sirius is 8.1×10^{13} km from the earth. If the speed of light is 3.0×10^{8} m/s, how many years does it take the light emitted by Sirius to reach the earth ?

[Ans : 8.56 years]

7. An aircraft travels at 350 km/h for 1.25 h and then 380 km/h for 1.80 h. What is its average speed for the complete journey ?

[Ans : 368 km/h]

8. What is the total average speed of a car if it travels 55.0 km in 1.50 h, then 85.0 km in the next 2.00 h, and finally 75.0 km in the next 1.80 h ?

[Ans : 40.57 km/h]

9. Determine the average velocity of an aircraft if it flies in a straight line and travels 1250 km due north in 2.20 h.

[Ans : 568 km/h north]

10. If an aircraft flies with a velocity of 650 km/h due west, what is its displacement after an elapsed time of (a) 3.00 h (b) 50.0 min (c) 45.0 s ?

[Ans : (a) 1950 km W (b) 542 km W (c) 8.13 km W]

11. A boy sees a flash of lightning and hears the thunder 8.0 seconds later. How far away is the storm if the speed of sound in air is 330 m/s, and the speed of light is 3.0×10^{8} m/s?

[Ans : 2.64 km]

12. What is the magnitude of the average acceleration of an aircraft if during take off it accelerates in a straight line from rest to 44.0 m/s in 11.0s ?

[Ans : 4.00 m/s^2]

13. What is the final speed of a racing car that accelerates in a straight line from rest for 8.00 seconds at 4.20 m/s^2 ?

[Ans : 33.6 m/s]

14. What is the average acceleration of a rocket that moves in a straight line from rest to a speed of 11500 km/h in 25.0 min ?

[Ans: 2.13 m/s^2]

15. If a ship changes its position from 360 km due West of a light-house to 240 km due West of the same light-house in 16 h, what is its average velocity ?

[Ans : 7.5 km/h East]

16. An electron accelerates in a straight line at 4.5×10^{10} m/s^2 in a cathode ray tube. If its initial speed is 2.5×10^{4} m/s, what is its speed after 3.0×10^{-6}s ?

[Ans : 1.60×10^{5} m/s]

17. Determine the acceleration of a car if it travels due South in a straight line and changes speed from (i) 7.70 m/s to 16.9 m/s in 8.00 seconds and (ii) rest to 45.0 km/h in 15.0 s ?

[Ans. (i) 1.2 m/s^2 south (ii) 0.833 m/s^2 south]

18. A person walks 3.00 km West and then turns around and walks 5.00 km East. If the total time of the walk is 2.50 h, determine (a) the total distance travelled, (b) the total displacement, (c) the average speed and (d) the average velocity.

[Ans : (a) 8.00 km (b) 2.00 km East (c) 3.20 km/h (d) 0.80 km/h East]

19. Determine the distance travelled and the magnitude of the acceleration of a train if it accelerates from 8.00 m/s to 28.0 m/s in 50.0 s.

[Ans : 900 m ; 0.400 m/s^2]

20. Determine the time that an aircraft spends during its take off run if it accelerates from rest at 3.00 m/s^2 to a final speed of 36.0 m/s.

[Ans : 12.0 seconds]

21. A car accelerates from 50.0 km/h to 125 km/h in 20.0s (a) What is the magnitude of its acceleration in metres per second squared ? (b) How far does the car travel while accelerating ?

[Ans : (a) 1.04 m/s^2 (b) 486m]

22. An electron in a cathode ray tube accelerates from rest to a speed of 415 km/s in an elapsed time of 1.50 μs. (a) What is its acceleration? (b) How far does it travel while accelerating ?

[Ans : (a) 2.77×10^{11} m/s^2. (b) 31.1 cm]

23. The driver of a car applies the brakes, bringing the car uniformly to rest in 4.00 s. (i) How far did the car travel after the brakes were applied, and (ii) What was the acceleration if the initial speed was 80.0 km/h ?

[Ans : 44.4 m; 5.55 m/s^2]

24. A car travelling at 80.0 km/h decelerates uniformly to 50.0 km/h in 8.00 s to pass through a speed zone. It then travels through the speed zone at 50.0 km/h in 18.0 s and accelerates uniformly back to 80.0 km/h in an additional 7.50 s. Determine (a) the accelerations of the car at each stage of the time period ; (b) the total distance that the car travels during this time.

[Ans : (a) -1.04 m/s^2 ; 0; 1.11 m/s^2 (b) 529 m]

25. A speeding motorist travelling at 115 km/h passes a stationary police patrol car. At the instant the patrol car is passed, it accelerates uniformly from rest to a speed of 135 km/h in 8.00s, and then maintains that speed until the speeder is caught. Determine (a) the acceleration of the patrol car, (b) the total time required for the police to catch the speeder, (c) the total distance that the chase lasted.

[Ans : (a) 4.69 m/s^2 (b) 26.85 (c) 854 m]

26. Plot a velocity versus elapsed time graph for the data in the following table :

Velocity in (m/s)	5.0	7.0	9.0	11.0	13.0	15.0
Elapsed Time in Seconds	0	1.0	2.0	3.0	4.0	5.0

(a) Is the motion uniformly accelerated ?

(b) Determine the acceleration from the graph.

(c) Find the displacement in the 5.0 s from the graph.

[Ans : (a) yes (b) 2.0 m/s^2 (c) 50 m]

27. Using the information in the following table, draw graphs of (i) distance versus elapsed time ; (ii) distance versus the square of the elapsed time.

Distance (m)	0	4.9	19.6	44.1	78.4	123	176
Elapsed Time (s)	0	1	2	3	4	5	6

28. Determine the slope and hence the formula from the graph in Fig. 1.55.

Hints :

[Slope (m) = $\dfrac{123\,m - 20\,m}{25\,s^2 - 4\,s^2}$; since the graph is a straight line so distance (s) $\propto t^2$]

[Ans : slope = 4.9 m/s^2
s = $4.9\,t^2$]

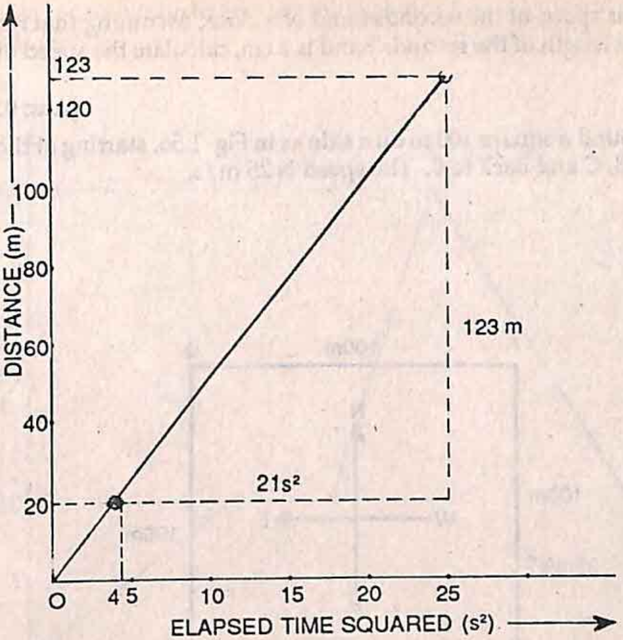


Fig. 1.55

29. From the data given below, plot the velocity-time graph and predict the nature of motion of the body :

Velocity(m/s)	1	2	3	4	5	6
Time (s)	1	2	3	4	5	6

From the graph

(i) Find the velocity of the body at the end of 3.5 s.

(ii) Calculate the uniform acceleration of the body.

[Ans: (i) 3.5 m/s (ii) 1 m/s^2]

30. Plot a graph between distance-time from the data given below. What can you say about the motion of the body ? How much speed will the body have at the end of 2.5s ?

Distance (m) →	7.5	15.0	22.5	30.0
Time (s) →	1	2	3	4

[Ans : (i) uniform velocity (ii) 7·5 m /s]

31. A train starts from Jullundur at 11.00 A.M. and reaches Ludhiana at 1.00 P.M. During the first half an hour it is uniformly accelerated to a velocity of 72 km/h. During the next one hour, its velocity remains 72 km/h. During the last half hour the brakes are applied and the train is uniformly retarded and stops at Ludhiana. Draw the velocity-time graph of the motion. Find the acceleration, uniform retardation and total distance between Jullundur and Ludhiana.

[Ans : 0.01 ms^{-2}; 0.011 ms^{-2}; 108 km]

32. (a) A car is moving on a straight road with uniform acceleration. The following table gives the speed of the car at various instants of time :

Speed (ms^{-1})	5	10	15	20	25	30
Time (s)	0	10	20	30	40	50

Draw the velocity-time graph by choosing a convenient scale. Determine from it :

(i) The acceleration of the car, (ii) the distance travelled by the car in 50 seconds.

(A.I.S.E.1982)

[Ans. (i) 0.5 ms^{-2} (ii) 875 m]

33. Calculate the angular speed of the seconds hand of a clock, assuming that it moves with a uniform angular speed. If the length of the seconds hand is 2 cm, calculate the speed of the tip of the seconds hand.

[Ans: 0.1047 rad/s; 0.209 cm/s]

34. A vehicle moves around a square 100 m on a side as in Fig. 1.56, starting at the corner marked 0 and proceeding past A, B, C and back to 0. The speed is 25 m/s.

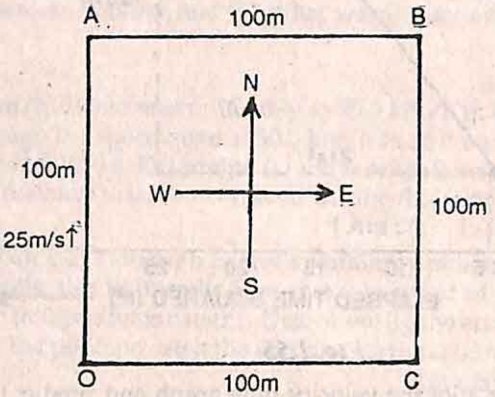


Fig. 1.56

Find the time that the object reaches points A, B, C and O, as well as the path travelled in that time and the displacement from 0.

[Ans : 4s, 100m, 100m north; 8s, 200m, 141m, 45° east of north; 12 s, 300 m, 100 m east; 16 s, 400 m, zero].

35. The speed of a train for the first minute of its motion is given by the following table :

Time in s	0	5	10	20	30	40	50	60
Speed in ms^{-1}	0	8.5	14.6	23	29.2	33.6	37	39

Plot the speed-time graph and from the graph find the distance travelled in the first minute.

[Ans :1571 m]

36. The relation between distance and time for a car starting from rest is given in the table :

Time is s	0	10	20	30	40	50	60	70
Distance in m	0	36	160	395	660	880	1040	1160

(a) Plot a distance-time curve for the first 60 s.

(b) Deduce the speed-time and acceleration time curves for the first 60 s.

37. The distance between two stations is 1800 m. An electric train starts from rest at one station with a uniform acceleration of 0.5 ms^{-2}; it comes to rest at the other station with a uniform retardation of 0.75 ms^{-2}, and the speed for the intermediate portion of the journey is constant. Sketch the general form of velocity-time graph.

38. A body starting from rest accelerates uniformly at the rate of 10 cm s^{-2} and retards uniformly at the rate of 20 cms^{-2}. Find, from the nature of graph of velocity versus time, the least time in which it can complete a journey of 5 km if the maximum velocity attained by the body is 72 km/h.

[Ans : 400 seconds]

39. A train moves from one station to another in two hours time. Its speed during the motion is shown in the graph below :

(Fig. 1.57)

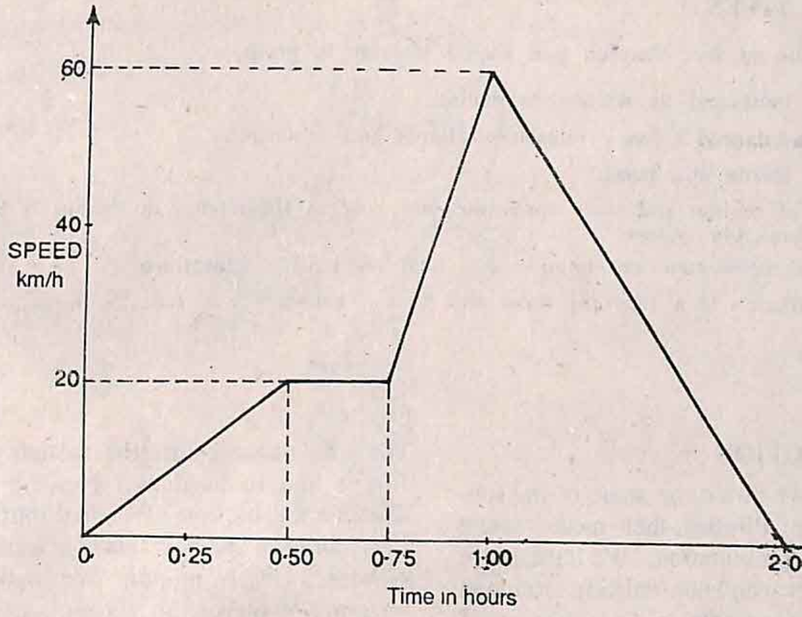


Fig. 1.57

Calculate

(i) maximum acceleration during the journey.

(ii) distance covered during the time-interval from 0.75 h to 1.00 h.

[Ans: (i) 160 km/h^2 (ii) 10 km]

[Hints :

Slope is greatest between 0.75 h and 1 h]

40. Two buses started simultaneously towards each other from towns A and B which are 480 km apart. It took the first bus travelling from A to B eight hours to cover the distance and the second bus travelling from B to A ten hours. Assuming the buses travel at constant speed, plot distance-time graphs for the two buses. From the graph find when the buses met after starting and at what distance, from town A.

[Ans: 4 h 27 min after starting and at 267 km from A]

41. A car covers the first half of the distance between two places at a speed of 40 km/h and the second half at 60 km/h. What is the average speed of the car ?

[Ans : 48 km/h]

□□

CHAPTER – 2

FORCE AND ACCELERATION

LEARNING OBJECTIVES :

At the completion of this Chapter, you should be able to grasp :

(a) The concept of force and its relation to motion.

(b) Balanced and unbalanced forces ; unbalanced forces and acceleration.

(c) The concept of inertia and mass.

(d) Newton's laws of motion and their application not only to the motion of earthly bodies but also to the motion of heavenly bodies.

(e) The concepts of momentum and impulse and their relationship with force.

(f) The idea that friction is a retarding force and it is a necessary evil (i.e., its importance in everyday life).

2.1 INTRODUCTION

In Chapter 2-1 we described some of the fundamental quantities of Physics, their measurement and their graphical representation. We have learnt how to describe uniform and non-uniform motion in terms of displacement, velocity and acceleration of moving bodies. We are now ready to study the causes that influence the motion of bodies. We shall introduce **Force** and **Mass** as new and most important concepts of Physics, in this Chapter. We have all probably wondered at one time or another why certain physical events occur. Why does the earth continue to move in its orbit about the sun instead of going off into the darkness of space ? Why do magnetic compasses in automobiles always point north ? Why do electrons in our TV sets strike the fluorescent screen with sufficient speeds to produce a picture on the screen ? In every case the answer is that forces act which control the motion of the objects in question. A gravitational force keeps the earth in its orbit around the sun. Electromagnetic forces align the compass needle in a north–south direction and accelerate the electrons in the TV tube. Other kinds of forces, the strong and weak nuclear forces, explain the stability (and the occasional instability) of atomic nuclei. Force is an essential factor in the construction of a bridge or the motion of an artificial satellite. Force is directly related to work and energy and energy includes heat, sound and light. We must know what force is in order to describe gravitation, magnetism and static electricity. The concept of force pervades the entire subject of physics.

In this Chapter we begin with the topic of force. We will also consider the motion produced by a forces and in particular Newton's laws which describe this motion. We shall introduce Galileo's idea of *inertia* and how this idea is incorporated into Newton's laws of motion. We shall discuss inertia in terms of objects at rest and objects in motion. When we combine the ideas of inertia and motion, we are dealing with *momentum*. Momentum refers to moving things.

2.2 CONCEPT OF FORCE (WHAT IS A FORCE ?)

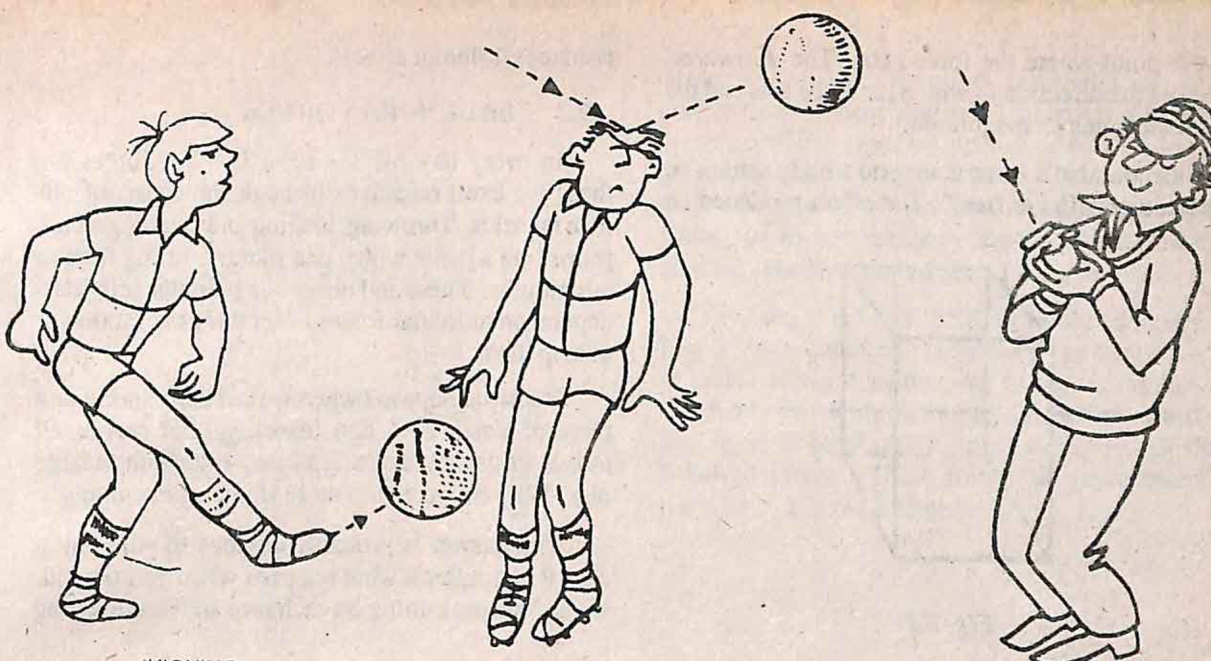
To start a ball rolling you throw it or kick it. In each case you are exerting a force on the ball (Fig. 2.1). Again you are exerting a force on the ball when you can head the ball to make it change direction. When you catch a cricket ball you stop its motion by exerting a force on it.

In all the above cases forces are being used *to change the motion* of a ball.

Of course it is possible to exert a force on something without moving it. You can lean against a wall, squeeze a rubber ball or twist a piece of plasticine but even then *part* of the object moves with respect to the rest.

Thus we find that in daily life, we often move objects from one place to another by pushing or pulling them or something has to be done to an object at rest in order to make it move, or to stop it, if it is in motion.

The scientific name for a cause that increases or decreases the speed of a body or changes its direction is force.



(KICKING) (HEADING) (CATCHING)

MASS IN MOTION

Fig. 2.1

A force is anything which causes a body to start moving when it is at rest, or stop it when it is moving, or deflect it once it is moving.

This is basically how a force is defined, although you will learn a more precise definition later in this Chapter.

Force applied on an object can, therefore, do three things :

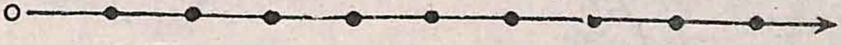


Fig. 2.2

(a) It can change the speed of the object making it move faster or slower. In other words, a force can bring about a change in the state of motion of a body.

(b) It can change the direction of motion of the object.

(c) It can change the shape of the object.

Can you give examples of forces which do any one of these three things, two of these and all three of these ?

FORCE AS A VECTOR QUANTITY :

A force cannot be completely described by its magnitude alone. The expression "*A force of 10 newtons*" is incomplete. The direction in which the force acts must also be known. Thus, a force is like a displacement–each requires a magnitude and a direction for its complete description. A force can, therefore, be represented by a vector; *force is a vector quantity.*

A vector used to represent a force is called a *force-vector*. Suppose we wish to draw a vector to represent a force of 10 newtons acting eastward upon point O. We select a suitable scale, and draw a line ten units long eastward from point O as shwon in Fig. 2.2. A force-vector is always represented as a *pull* upon a point where the force acts. The arrowhead indicates the direction in which the force acts and the length indicates its magnitude.

We note that a force acting on a body cannot be *displaced parallel to itself*. The effect produced on a body by an applied force depends not only on its magnitude and direction *but also on the point where the force is applied.*

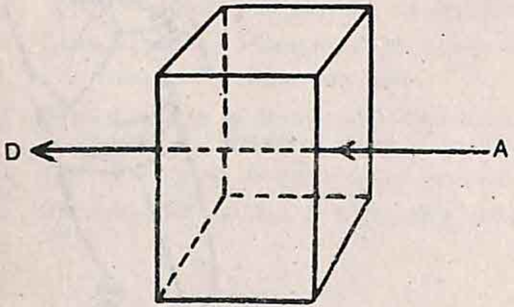


Fig 2.3

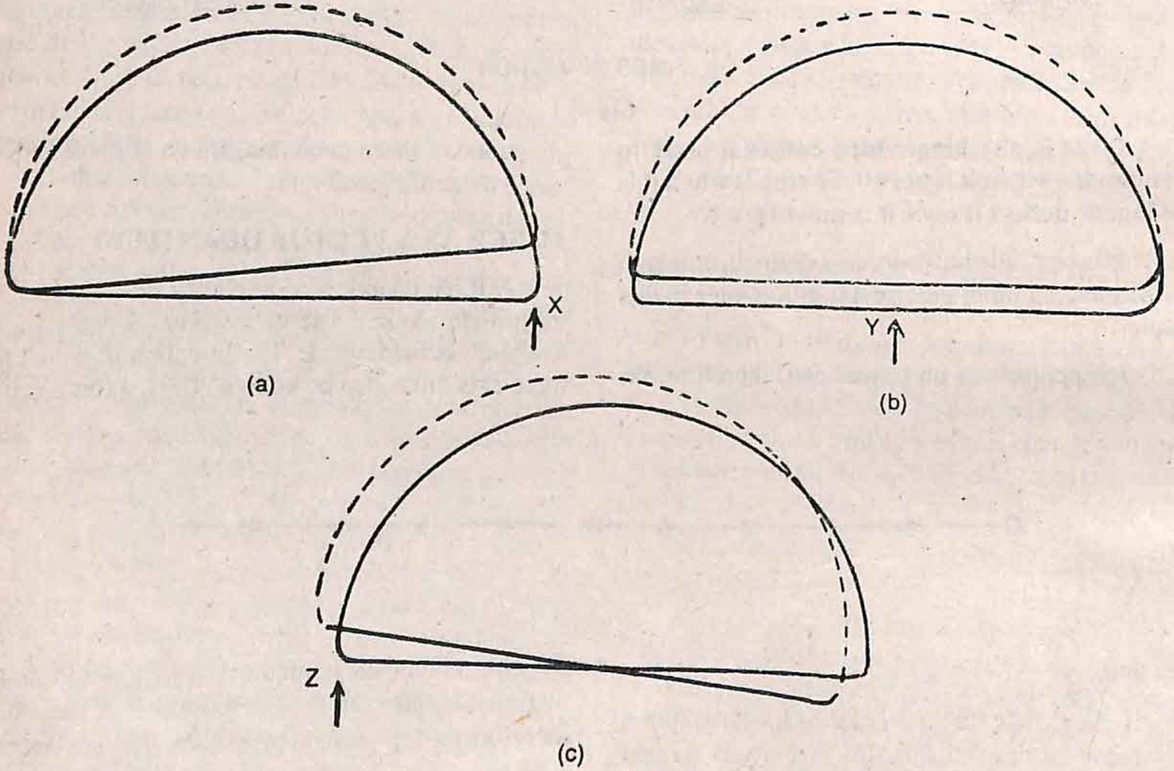


Fig. 2.4 Line of action of a force

If you push a body with nearly the *same* force with your finger at X or Y or Z [Fig. 2.4 (a), (b), (c)] the result will be different in each case. A force of same magnitude applied at three different points produces different effects.

2.3 BALANCED FORCES

In every day life the most familiar forces are those we exert ourselves through the action of our own muscles. Throwing, kicking and catching a ball, propelling a pellet with a pea shooter, lifting food to our mouths. These and many other similar activities, depend on muscular forces to set things in motion or to stop them.

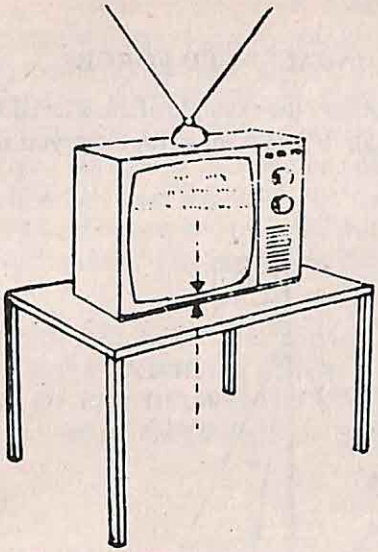
But what happens when we stretch a spring or a piece of elastic ? Motion ceases, yet our nerves tell us that we are still exerting a force–often quite a large one. Why do we get no more starting or stopping?

The answer is probably obvious to you, but in case it is not,think what happens when you tie your shoe. You are pulling on each lace and thus exerting a force on your foot, yet foot does not begin to move.

Of course you are exerting several forces on your foot–one in each lace, and one from your leg–and they cancel out. The total force is zero.

When we add up forces in this way to get zero, we have to take into account not only the size of the forces, but also the directions in which they act. A body tries to start moving in the direction of the force. If two equal forces act in opposite directions they *just balance and produce no motion*. **Forces which just balance and produce no motion are called balanced forces** and they are said to be in *equilibrium*. The resultant of such forces in zero.

The world is literally full of balanced forces. In Fig. 2.5 two balanced forces keep the television set at rest. If we consider the forces acting on the lineman's feet in Fig. 2.6 as a single force we can say that he is in equilibrium under the action of three balanced forces. These forces are represented by three arrows in the diagram.



Force of gravity on T.V. is balanced by upward push of the table

Fig. 2.5

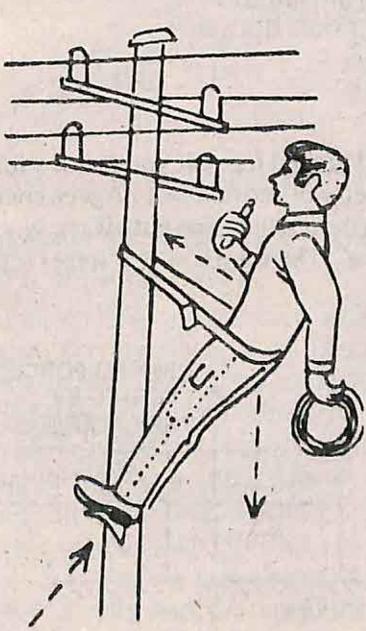


Fig. 2.6

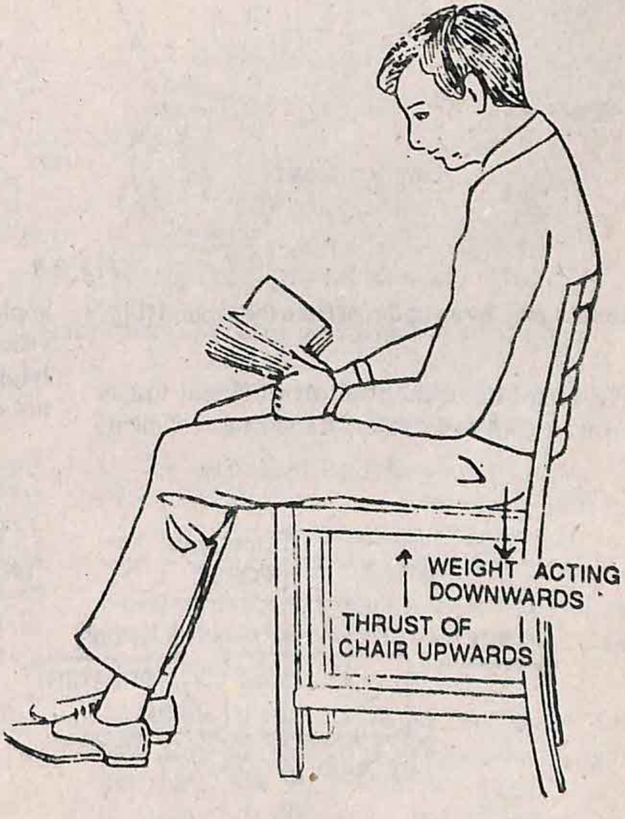


Fig. 2.7

As you sit reading this book, the force of gravity pulling you towards the earth is just balanced by the support of the chair on your body (Fig. 2.7). The chair itself is held steady by an upward push of the floor.

A flagstaff is held steady by the pull of its guy ropes and, again, by an upthrust from the ground (Fig. 2.8).

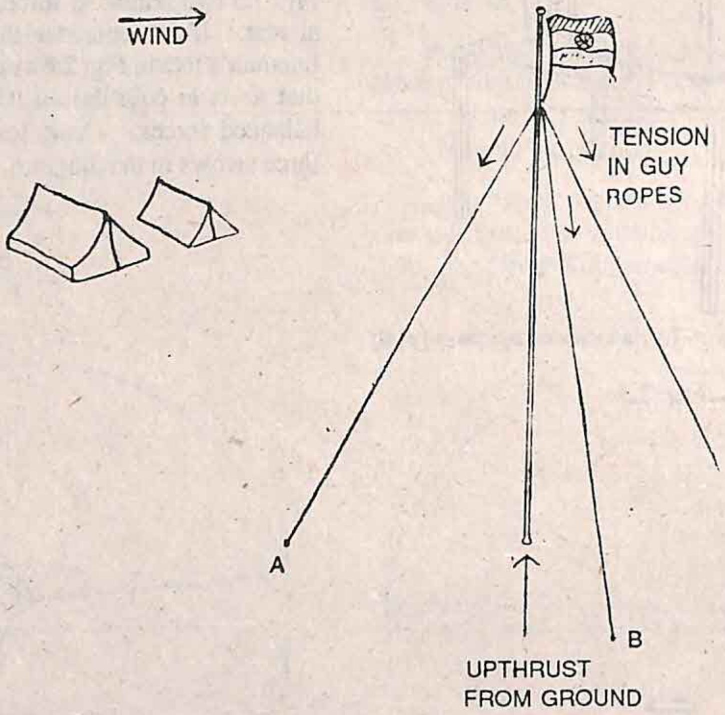


Fig. 2.8

We soon lose count of all the different forces around us. Luckily we can forget about most of them, since they simply cancel each other out and produce no motion.

2.4 UNBALANCED FORCES

Consider the example of the television set again (Fig. 2.5). If you want to lift it up, you will have to apply additional force. If you remove force, the television set will move down. Again, consider a brick lying on the ground. You push it gently so that it does not move. There are now four forces acting on it (i)

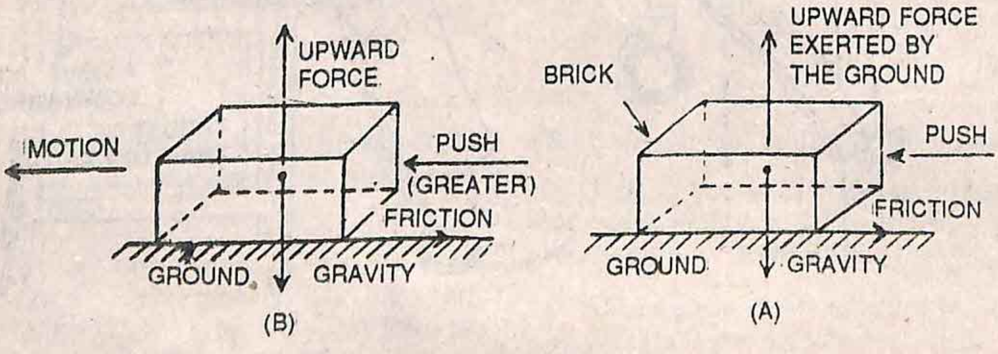


Fig. 2·9

the force of gravity pulling it towards the centre of the earth,(ii) force exerted by the ground on the brick, which balances the force of gravity and keeps the brick on the ground,(iii) your push, and (iv) the force of friction opposing the push. The resultant of all these forces is zero and the forces are said to be balanced. If you increase or decrease one of these forces (say if we increase the push), the resultant force will no longer be zero and the brick will begin to move. In such situations we say that the forces are *unbalanced.*

Unbalanced forces *are those forces which produce change in state of motion of a body.*

Some of the forces (balanced as well as unbalanced) involved in riding a bicycle are shown in Fig. 2.10.

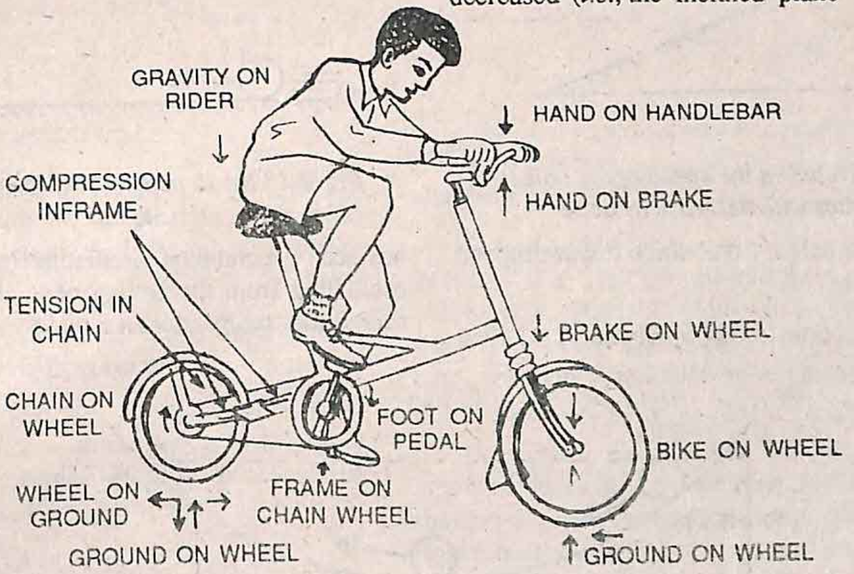


Fig. 2.10 Balanced and unbalanced forces in riding a bicycle

2.5 *GALILEO'S EXPERIMENTS ON THE MOTION OF OBJECTS :

It was Galileo (1564-1642) a foremost scientist of the sixteenth century who, on the basis of his experiments (some of which are given below), deduced that *objects move with constant speed when no forces act on them.* No body at that time believed this. If we look around, we would also hardly believe this as it is contrary to common experience. A book on a table, when given a push, does not continue to move forever. It moves some distance and quickly comes to rest. A rickshaw on a road has to be constantly pulled or pushed to keep it in motion. A single pull or push will not take it far. If we do not look carefully, we too, like the ancient Greeks, would be tempted to believe that bodies come to rest when no forces act on them. How did Galileo come to the correct conclusion that the Greeks were wrong? Let us look at some of his observations in his experiments.

Galileo first observed the motion of objects on an inclined plane. He noted that when objects move down an inclined plane, their speed *increases* [Fig. 2.11(a)]. He also noted that when objects move up an inclined plane, their speed *decreases* [Fig. 2.11(b)]. Galileo further observed that when the angle of the inclined plane with the horizontal was decreased (*i.e.*, the inclined plane was made *less steep*), the increase in the speed of the object moving down the plane also got decreased (Fig. 2.12).

He then asked the following question : What would happen if the plane were inclined neither up or down ? That is, what would happen if the ball moved on a *flat surface* (Fig. 2.13) ? Does speed change ? Well, the answer was obvious to him. *Its speed would neither increase nor decrease. Its speed would remain constant.*

Galileo performed another experiment. But this time not with real balls and real planes but with imaginary ones. He thought that if a ball were made to fall along the sides of hollow hemisphere it would

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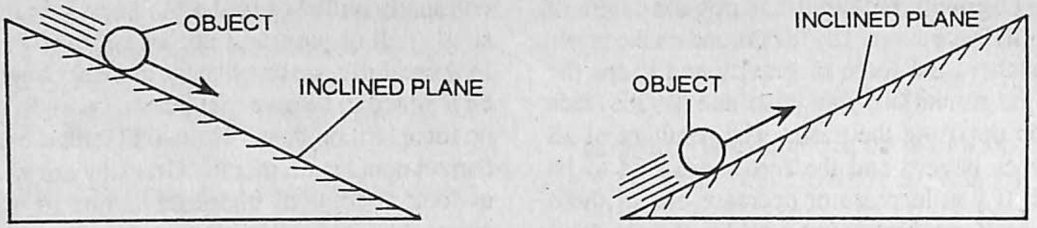
* For further knowledge only.



Slope downward–speed of the object increases

Slope upward–speed of the object decreases

Fig. 2.11

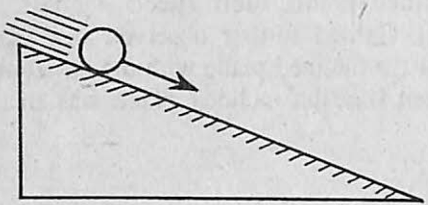


Fig. 2.12 Increase in the speed of the object-decreases with decrease in slope

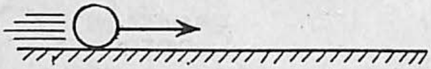


Fig. 2.13 No slope–Flat surface–no change in speed.

always reach the height from which it was dropped [Fig 2.14].

How did he come to this conclusion ? Galileo has seen a pendulum oscillating (a hanging lamp oscillating from the ceiling of a church) and observed that the pendulum always rises to the same height on either sides of its mean (or rest) position [Fig. 2.15]. The hemisphere performs the same function as the string of the pendulum. He then asked what would happen if the vessel were shaped as in Fig. 2.16(a) and said that it would reach the same height, but travel a longer distance in doing so. Notice that the more we decrease the slope at the other end of the vessel, the further the ball has to travel to reach the same height [Fig. 2.16(b)]. How far do you think the ball would travel if you decrease

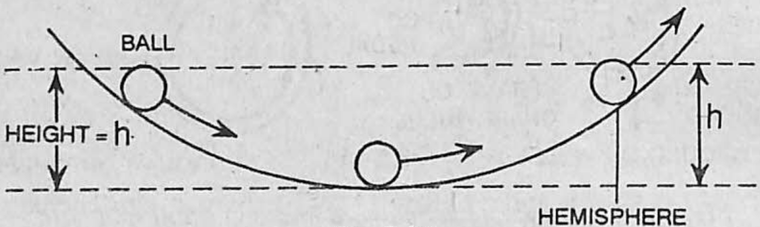


Fig. 2.14

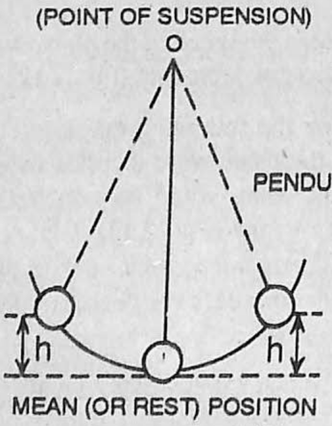


Fig. 2.15

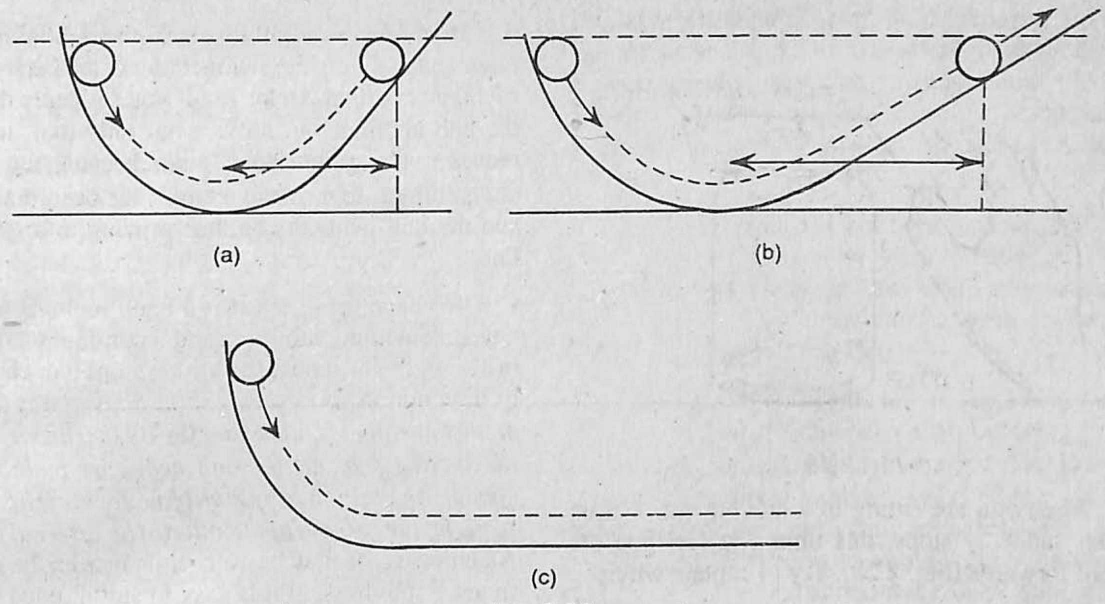


Fig. 2.16

the slope to that of Fig. 2.16(c) ?

Obviously the ball would have to travel an infinite distance to attain the same height. This could happen only if the speed of the ball on the flat surface remains unchanged.

Thus on the basis of the above observations, Galileo arrived at a startling conclusion :

"An object moving in a straight line with a constant speed will continue moving in the same straight line with the same speed in the absence of an external force."

2.6 INERTIA AND MASS

We know that objects that are not moving do not start moving by themselves. For example a football will not move unless it is kicked. Things that are at rest seem to stay there.

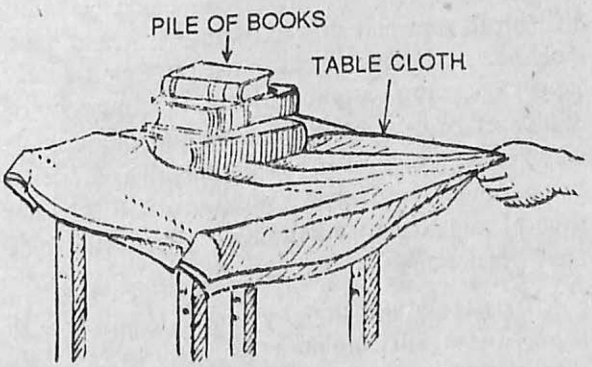


Fig. 2.17

Spread a table-cloth on a table and arrange a pile of books on it. Hold one edge of the table-cloth and pull quickly. The table-cloth will come off, leaving the pile of books undisturbed. The pile of books tends to remain at rest even when the thing on which it is resting is moved (Fig. 2.17).

Place a fifty paise coin on a small piece of cardboard and place the cardboard on an open jar so that the coin is directly over the mouth of the jar. Use one finger to flick the piece of cardboard away. You will notice that the coin drops into the jar. This shows that the coin tends to remain in its position of rest (Fig. 2.18).

There are other examples of things wanting to stay in place. When you are sitting in a car or train which starts suddenly you feel you are jerked backwards. In fact, you are not jerked backwards but your seat, which is in contact with the cushion is forced to move forwards with the car or train and the upper part of your body, which tends to remain at rest, is left behind (Fig. 2.19).

Generally things do not want to move if they are at rest. Nor do they want to stop once they are moving.

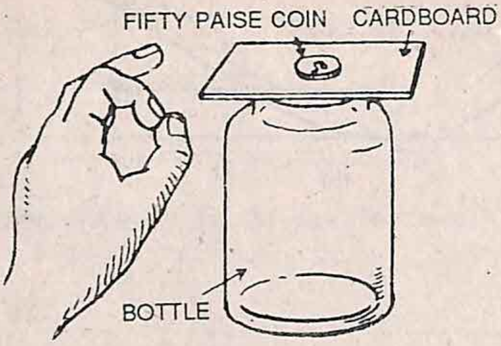


Fig. 2.18

When you are sitting in a moving car or train which suddenly stops, this time you feel you are jerked forwards (Fig. 2.20). Try to explain why you have that feeling, bearing in mind the explanation of illustration of Fig. 2.19 given above.

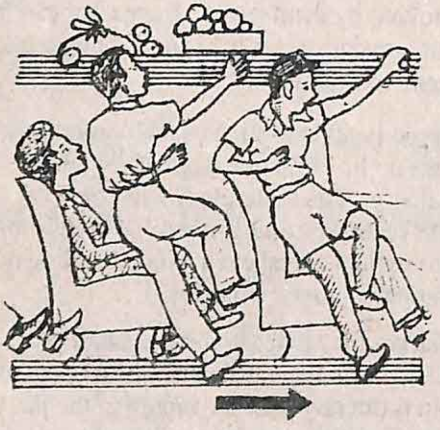


Fig. 2.19 Train starts suddenly

Have you ever watched a person trying to board, or to alight from a moving bus or train ? It is a dangerous practice and should not be copied. When boarding a moving train he does not just stand by and hold the door but first runs alongside with about the same speed as the train, and then jumps. When alighting from a train he does not just leap down and stop dead, but continues to run alongside the train after leaping down. If he stopped at once, his feet would come in contact with the ground suddenly and rest, but the other parts of his body would continue moving, so that he would fall headlong. But by running along as he comes down, gradually slowing down before stopping, he prevents a fall.

If you fasten a ball to a string and, holding the other end of the string, swing it round, the ball moves round in a perfect circle; but if you suddenly drop it the ball continues to move ; not only that, it now moves in a straight line. This is because the thing compelling it to move in a circle has been removed and the ball tends to continue moving in a straight line.

We have thus seen that a body remains at rest unless something moves it, and it continues to move in a straight line unless something stops it or changes its direction. *This tendency of the body to stay at rest or stay moving is called* **inertia** *By inertia we mean the inertness of matter and hence its inability to change its position of rest or of uniform motion in a straight line without application of an external force.* An empty tea trolley has very little inertia. It is easy to get it moving and it is easy to stop it once it has started. If you load the trolley with heavy things its inertia would be much greater. It would be more difficult to start and stop it because it would have more *mass*. Massive objects have more inertia than lighter ones. In fact mass, which is the quantity of matter in a body, is a numerical measure of inertia. If a body has more mass, it has more inertia. A cricket ball has more inertia than a shuttle cock. It is harder to accelerate a truck than a small car because the truck has a greater mass.

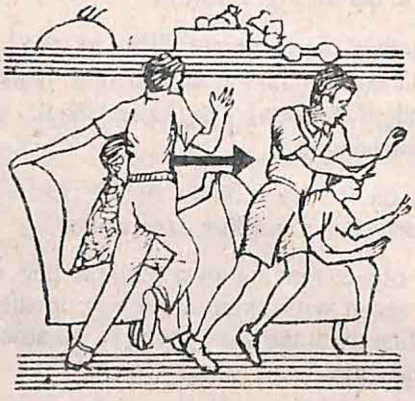


Fig. 2.20 Train stops suddenly

To start and stop things you need to pull or push them. These pulls and pushes are known as forces. If you hold two magnets close to each other you can sometimes feel them pull and sometimes push against you.

A force is needed to start a body moving and to slow down a moving body. *In other words the force overcomes the inertia of the body.*

2.7 NEWTON'S LAWS OF MOTION

In 1642, several months after Galileo died, Isaac Newton was born. By the time Newton was 23, he developed his famous laws of motion, which completed the overthrow of the Aristotelian ideas that had dominated the thinking of the best minds for 2000 years. In this article we will consider these laws in order. The first is a restatement of the concept of inertia as proposed earlier by Galileo. The second law relates acceleration to the cause that produces it *i.e.*, force. The third is the well–known law of action and reaction. There three important laws first appeared in one of the most important books of all time, Newton's famous *Principia Mathematica* (1686). Newton's statement of the laws of motion was one of the most important developments in physics. These laws form the basis of what is now called *classical* or *Newtonian mechanics*. It was not until the twentieth century that Newton's laws proved to be inadequate because they could not fully describe the motion of extremely small atomic-sized particles, or particles that travel close to the speed of light (3×10^8 m/s). However, because of their mathematical simplicity and accuracy, the laws of classical mechanics are still used to predict and describe the motions of many objects, such as cars, aircraft, planets and satellites.

NEWTON'S FIRST LAW OF MOTION : THE LAW OF INERTIA

Aristotle's idea that a moving object must have a force exerted on it was completely turned around by Galileo, who stated that in the *absence* of a force, a moving object will continue moving. The tendency of things to resist changes in motion was what Galileo called *inertia.* Newton refined Galileo's idea and made it his *first law*, also appropriately called the *law of inertia.* Newton's first law of motion concerns the effect of balanced forces on bodies. It is stated as follows :

"Every body continues in its state of rest or of uniform motion in a straight line, unless it is compelled to change that state by an unbalanced force impressed upon it."

The key word in this law is *continues* : a body *continues* to do whatever it happens to be doing unless a force is exerted upon it. If it is at rest, it *continues* in a state of rest. If it is moving, it *continues* to move without turning or changing its speed. In short, the law says that an object does not accelerate of itself ; acceleration must be imposed against the tendency of an object to retain its state of motion.

The first part of this law seems reasonable and in agreement with our everyday experience. We know fully well that bodies at rest will remain at rest until some external force causes them to move. Everyone recognizes this fact.

The second part of this law is somewhat more subtle. Restated, the law says that a moving body would continue moving in a straight line forever unless some external force were applied to it. Common experience seems to contradict this. We know that nothing continues to move forever without change. A ball rolled across the ground soon stops. A metal object sliding across a smooth table eventually slows and stops. There are many ohter cases such as this. However, each of the examples cited is not a valid test of Newton's first law of motion. A force is acting on each of these bodies trying to stop its horizontal motion. It is the force of friction. We all know that, the more precautions we take to eliminate this force, the less rapidly the moving object is brought to rest. Newton mentally generalized this observation to the case where no friction forces exist and concluded that, if this case were possible, the moving object would never stop. Although an example of perfect unchanging motion has never been attained, of course, all our experience leads us to believe that Newton's conjecture, stated as a law of nature, is valid.

Newton's first law of motion implies that all matter possesses inertia. The greater the inertia of an object, the larger is the force required to bring a change in its state of rest or of uniform motion. Thus Newton's first law of motion is also called **law of inertia.** A few simple examples given earlier to illustrate the property of inertia of rest and inertia of motion are also examples of Newton's first law of motion.

According to Newton's first law of motion, we have seen, that a body remains at rest unless something moves it, and it continues to move in a straight line unless something stops it or changes its direction. Scientists call that something force. In other words, *Newton's first law of motion gives us the definition of force.* The force is the cause of change of position of rest or of uniform motion in a straight line. The force may be applied in the form of a push or pull. It may be defined as follows :

Force is a push or a pull which produces or tends to produce, destroys or tends to destroy motion in a body.

It should be very clearly understood that the force must act on a body or a system of bodies from outside, *i.e., it must be an unbalanced force.* An *internal* force cannot cause any change of state of a body. It is impossible for a man to lift himself by putting his feet in two buckets and pulling up their handles.

NEWTON'S SECOND LAW OF MOTION

(*Unbalanced force* and *Acceleration*)

We have earlier discussed about unbalanced (or net or resultant) forces and we know that they produce change in motion of a body. Newton's first law of motion is rather a simple statement of behaviour which is familiar to all of us. Newton, through his second law of motion, established a relation between force and change of motion. Newton's second law of motion is stated as follows :

"If an unbalanced force acts upon a body, that force will produce an acceleration of the body in the direction of the force. The magnitude of the acceleration is in direct proportion to the magnitude of the unbalanced force, and in inverse proportion to the mass of the body."

If $\vec{F}$ = unbalanced force or external force

m = mass of the body

$\vec{a}$ = acceleration produced in the body

then according to Newton's second law of motion,

$$\vec{a} \propto \frac{\vec{F}}{m}$$

The above proportionality may be written as

or $\vec{F} \propto m\vec{a}$

or $\vec{F} = km\vec{a}$

where k is the constant of proportionality. ...(1)

We define the unit force to be that force which produces a unit acceleration in a unit mass of a body. That is

$\vec{F} = 1$ if

$m = 1$

$\vec{a} = 1$.

In terms of this unit of force,

$1 = k.1.1$

or $k = 1$

Putting k = 1 in eq. (1), we get the most important fundamental equation of mechanics :

$$\boxed{\vec{F} = m\vec{a}}$$

Remember that

Force = Mass × Acceleration

$$\text{or Mass} = \frac{\text{Force}}{\text{Acceleration}}$$

$$\text{or Acceleration} = \frac{\text{Force}}{\text{Mass}}$$

Newton's second law of motion gives us a *measurement of force* in terms of mass and acceleration. This law tells us what happens when an unbalanced force is exerted on an object.

Units of force :

In the SI (Systeme International) system, absolute unit of force is called *newton*. It is denoted by the symbol N. It may be defined as follows :

One **newton** *is that resultant or unbalanced force which acting on a mass of 1 kilogram produces an acceleration of one metre per second per second.*

$$1\text{ N} = 1\text{ kg. }1\text{ m/s}^2$$
$$= 1\text{ kg m/s}^2.$$

In the c.g.s. system, absolute unit of force is **dyne**. It may be defined as follows :

One **dyne** *is that resultant force which acting on a mass of one gram produces an acceleration of one centimetre per second per second.*

$$1\text{ dyne} = 1\text{ g. }1\text{ cm/s}^2$$
$$= 1\text{ g cm/s}^2.$$

Since $1\text{ N} = 1\text{kg. }1\text{ m/s}^2$

$\therefore$ $1\text{ N} = 10^3\text{ g. }10^2\text{ cm/s}^2$

$= 10^5\text{ g cm/s}^2$

or $\boxed{1\ \mathrm{N} = 10^5\ \text{dynes}}$

Note :

Force (N) = Mass (kg) × Acceleration (m/s^2)
Force (dyne) = Mass (g) × Acceleration (cm/s^2)

NEWTON'S THIRD LAW OF MOTION (ACTION AND REACTION)

Newton's third law of motion appears to have little connection with the first two. It states that

"to every action there is an equal and opposite reaction" ; or that when two bodies act upon each other, the action of the one is equal in magnitude and opposite in direction to the reaction of the other upon it. More briefly, but less exactly, action and reaction are equal and opposite.

The students should notice that Newton's third law of motion deals with *two distinct* bodies. An action force is exerted on one (body A) by the other (body B), while a reverse reaction force is exerted by A on B.

To illustrate this law more fully, consider the following examples :

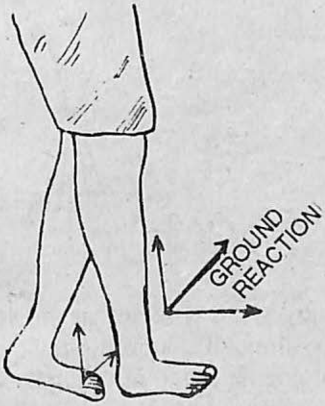


Fig. 2.21

(1) When you walk, your foot pushes backward on the earth and the earth exerts an equal and opposite force forward on you (Fig. 2.21). Two bodies and two forces are involved. The comparatively small force you exert on the large mass of the earth produces no noticeable motion of the earth, but the equal force it exerts on your very much smaller mass causes you to move. It is important to note that the equal and opposite *forces do not act on the same body* if they did, there could never by any resultant force and all motion would be imporssible.

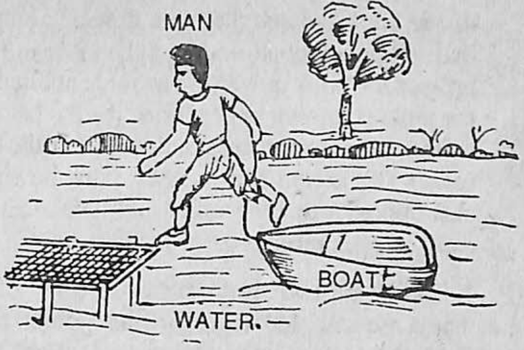


Fig. 2.22

(2) Whenever a person steps from a rowing boat, he pushes backward on the boat (the action) which moves accordingly whilst the boat pushes the person forward (the reaction) (Fig. 2.22). The forces are equal in size, opposite in direction and act simultaneously on the person and the boat.

(3) When there is a load on a hand, the hand is subjected to a downward force by the weight of the load, and the hand also applies an equal and opposite force on the load. If now, the hand is moved up with the load, an additional force must be applied to the hand.

(4) If a man raises a weight by a string tied to it, the string exerts on the man's hand exactly the same force as it exerts on the weight but in the opposite direction.

(5) A ladder leaning against a wall presses on it and tends to push the wall back. This action is equal and opposite to the counter thrust called the reaction, exerted on the ladder by the wall which keeps the ladder in position.

(6) A boatman presses one end of a bamboo pole against the ground and the boat on the water moves forward. Here the bamboo pole presses the earth and the earth sets up the reaction force along the pole in the opposite direction. The component of the reation force in the horizontal forward direction communicated to the boat through the boatman makes the boat moves forward.

(7) When a magnet attracts a piece of iron, the iron also attracts the magnet with an equal and opposite force. If the action of the magnet on the iron is the action-force, that of the iron on the magnet is the reaction-force.

(8) Consider a book lying on the table. The weight

of the book presses the table downwards and that is known as an *action*. The table in turn presses the book upward. The force applied by the table is known as *reaction*. As the book is neither moving upward nor downward, the two forces *i.e.*, action and reaction must be equal and opposite to each other and hence cancel each other completely.

(9) X and Y are two spring balances (Fig. 2.23). They are coupled together and pulled part. Both the springs show the same reading. X is pulling Y towards it (action) and Y is pulling X towards it with an equal and opposite force (reaction). Here action and reaction are interchangeable.

(10) When a boatman wants to reach the bank, he tries to pull the bank towards him (action) with the help of a rope tied to a peg on the bank. The bank pulls the boat towards it with an equal and opposite force (reaction).

(11) The birds, while flying, push the air downwards with their wings (action). The air exerts an equal and opposite force on the birds in the upward direction (reaction).

(12) In the rockets (Fig. 2.24). the burnt gases are exhausted out in the vertically downward direction with a great force (action). These gases exert and equal and opposite force on the rocket in the vertically upward direction (reaction).

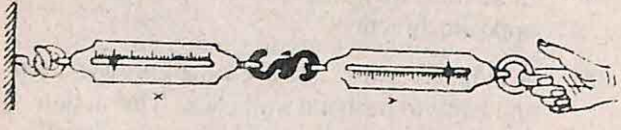


Fig. 2.23

Jet aircrafts also work on the same principle.

(13) When a bullet is fired from a rifle with a certain force (action), there is an equal and opposite force exerted on the rifle in the backward direction (reaction). So the gun recoils back.

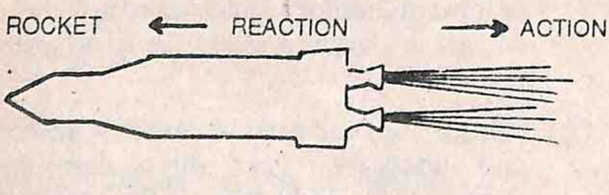


Fig. 2.24

(14) The moon is attracting the earth with a certain force (action). The earth also attracts the moon with an equal and opposite force (reaction).

(15) The swimmer pushes the water in the backward direction with a certain force (action). Water pushes the man forwards with an equal and opposite force (reaction).

(16) Fill a balloon with air. Hold it with its mouth downwards (Fig. 2.25). Release the balloon. The air rushes out vertically downwards (action). The balloon moves vertically upwards (reaction).

(17) In a rotating fountain, a central pipe is fitted with four small pipes having fine nozzles at the ends (Fig. 2.26). Water rushes out of the nozzles (action). The pipes move in the opposite direction (reaction). The principle is used in the fountain to sprinkle water around.

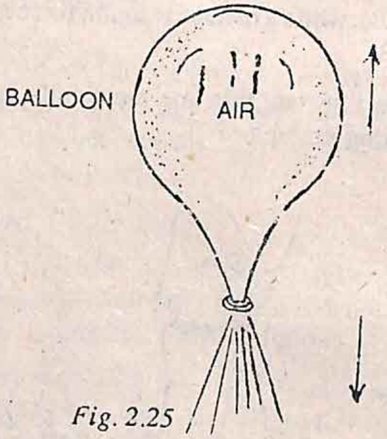


Fig. 2.25

(18) In a toy steam engine, steam is allowed to escape through a fine nozzle (action). The steam engine move in the opposite direction

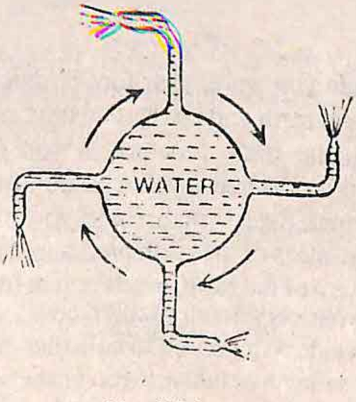


Fig. 2.26

(reaction). This principle is also used in toy streamships. Originally Newton used this principle in his automobile.

From these examples it is clear that the action and reaction act on *different* bodies. If action and reaction were to act on the same body they would add up to zero. *Forces always occur in pairs.*

2.8 MOMENTUM

It is common experience to us all that a moving object possesses a quality which causes it to exert a force upon any one who tries to stop it. The faster the object is travelling, the harder it is to stop. In addition, the more massive the object is, the more difficulty we have in stopping it. For example, a man travelling 10 m/s in an automobile is much less easily stopped than a child on a kiddie car travelling at the same speed.

Newton called this quality of a moving body as the *"motion"* of the body. We to-day term it the **momentum** of the body. Momentum is considered to be a measure of the *"quantity of motion"* of a body and it is defined as **the product of mass and velocity.**

Often the symbol $\vec{p}$ is used for it. That is in symbols

$$\boxed{\vec{p} = m\vec{v}}$$

where m is the mass of the body and $\vec{v}$ its velocity.

The direction of the momentum, which is a *vector* quantity, is the same as the direction of the velocity. The unit of momentum is kg m/s or newton-second.

MOMENTUM AND FORCE

Obviously the momentum of a body is the result of forces which accelerated the body from rest to velocity v. Similarly, if we are to slow down the body (*i.e.*,cause it to lose momentum), we must apply a retarding force to it. A large retarding force will cause the body to lose more momentum in a given length of time than will a small retarding force. We now wish to find the exact mathematical relation between force and change of momentum.

Consider the acceleration of a body by a constant force F as shown in Fig. 2.27. The force is the net unbalanced force on the body and will cause a uniform acceleration $\vec{a}$ in the x direction,

$$\vec{a} = \frac{\vec{F}}{m} \quad \text{... (i)}$$

If the body had an original velocity u and the force acts for a time t, our motion equations yield the result

$$\vec{v} = \vec{u} + \vec{a}t$$

or

$$\vec{a} = \frac{\vec{v} - \vec{u}}{t} \quad \text{... (ii)}$$

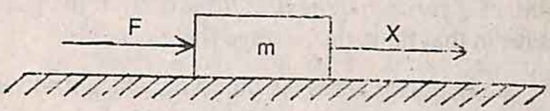


Fig. 2.27

Putting (i) in (ii) and rearranging leads to the result

$$\vec{F} = \frac{m\,(\vec{v} - \vec{u})}{t}$$

or

$$\boxed{\vec{F} = \frac{m\vec{v} - m\vec{u}}{t}} \quad \text{....(iii)}$$

Here, m $\vec{u}$ is the initial momentum $\vec{p_1}$ of the body m $\vec{v}$ is the final momentum $\vec{p_2}$ of the body.

$\vec{p_2} - \vec{p_1} = m\vec{v} - m\vec{u}$ is the change in momentum that occurred in the time interval t. The change per unit time, or rate of change of momentum

is $\frac{(m\vec{v} - m\vec{u})}{t} = \frac{\vec{P_2} - \vec{P_1}}{t}$ Thus equation (iii) may be expressed in words as

Force equals rate of change of momentum. Another way of expressing this is that net forces cause changes in momentum.

Newton's second law of motion is intimately connected with change in momentum. According to momentum form of Newton's second law of motion

" the rate of change of momentum of a body is equal to the unbalanced force acting on it".

This form of the law is actually more basic than the former

$$\boxed{\vec{F} = m\vec{a}}$$

Impulse :

There are some situations in which the initial and final momentum may be the only measurable quantities. For example, a golf ball is initially at rest ; after being hit, it has a measurable speed (using proper techniques). The force is very large and acts for a very short interval. The mass of the golf ball is easily found, so the change in momentum can be found. Another situation is that of a ball that strike's a person's head and bounces off. The change in momentum of the ball can be found. In each of these situations we say that there has been a blow or an **impulse.**

The word impulse is defined in physics as *the product of force and the time force acts.* If the force varies in that time, the average force is used.

An impulse causes the object on which it acts to change its momentum, and the amount of change in momentum is found from Newton's second law of motion. Use it in the form

$$F = \frac{mv - mu}{t} = \frac{\overrightarrow{p_2} - \overrightarrow{p_1}}{t}$$

or $$\boxed{Ft = \text{Impulse} = m\upsilon - mu = \overrightarrow{p_2} - \overrightarrow{p_1}}$$

The left hand side of this equation is the impulse and the right handside is the change in momentum of the body on which the impulse acted. In words, the equation says that **impulse equals change in momentum**. An impulse may be measured by the change in momentum caused by it. This can be useful in situations in which it is not possible to measure the size of the force (and it may vary) or the time. One example is that of a ball being struck by a bat.

Unit of impulse is *newton second* (NS) or kg m/s.

2.9 FRICTION

The surfaces of bodies are never perfectly smooth. Whenever a very smooth surface is seen under a microscope, it is found to have roughnesses and irregularities which cannot be detected by ordinary touch (Fig. 2.28). If a block of one substance be placed upon a level surface of the same or of different material, there is a certain degree of interlocking of the minutely projecting surfaces. This involves no force so long as the block does not move or tend to move tangential with respect to the surface on which it rests. When the block is gently pushed, it does not move because a force opposing the push is called into play which prevents motion. This opposing force arises as a reaction to the applied force and acts in the opposite direction. *This force which is brought into play when one body tends to move over another and which* **always opposes** *motion, is called the* **force of friction** *or simply* **friction.**

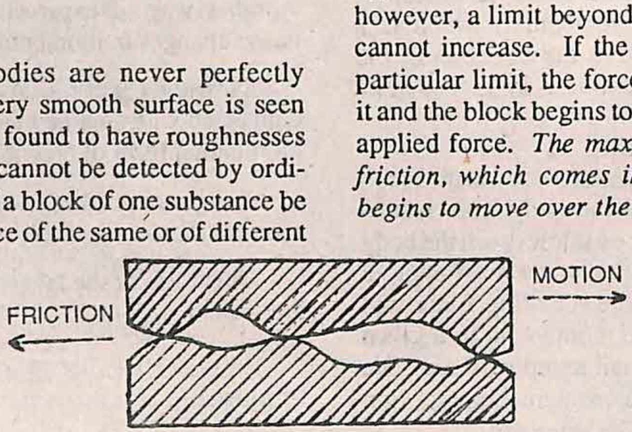


Fig. 2.28

The force of friction is caused by the interlocking of the irregularities of the surfaces in contact. The motion of one surface over the other requires the overcoming of interlocking obstacles which may be achieved by the slight lifting of the moving body or the smoothening of the irregular projections or the filling up of the irregularities by a suitable lubricant. If the surfaces are polished, the force of friction between them considerably decreases.

Friction–a self-adjusting force:

Consider a block of wood lying on a plane horizontal table and push the block lightly with the hand. The block does not move which shows that the force of the hand is being *exactly* balanced by the force of friction acting horizontally in the opposite direction.

Now push the block a little harder ; it is still found to be in equilibrium. Obviously, the force of friction has increased itself so as to become equal and opposite to the applied force. Thus the force of friction has a remarkable property of adjusting its magnitude so as to become exactly equal to the applied force tending to produce motion. There is, however, a limit beyond which the force of friction cannot increase. If the applied force exceeds this particular limit, the force of friction cannot balance it and the block begins to move in the direction of the applied force. *The maximum value of the force of friction, which comes into play when a body just begins to move over the surface of another body, is known as* the **limiting friction**. When there is no relative motion between the two surfaces, the friction is a **static friction** and it can have any value from zero to the limiting friction. Thus within the limiting friction, the force of friction is a *self-adjusting force i.e.,*as much of it comes into play as is just sufficient to prevent motion. Once the applied force exceeds this limit, the body begins to move under the action of the resultant force.

Again friction is capable of adjusting itself not only with regard to its magnitude but also to the direction of the applied force. If, in the above case, the hand begins to exert from the opposite direction, the friction also changes its direction and opposes the motion of the block.

Thus friction is a peculiar force. *It has no independent existence of its own* but arises when one body tends to move over the surface of another and always acts in a direction opposite to that of the motion.

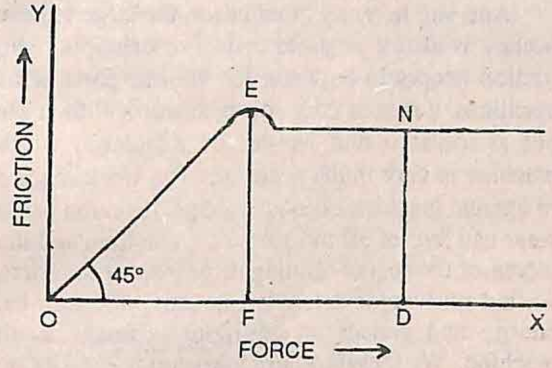


Fig. 2.29 Sliding friction is less than limiting static friction.

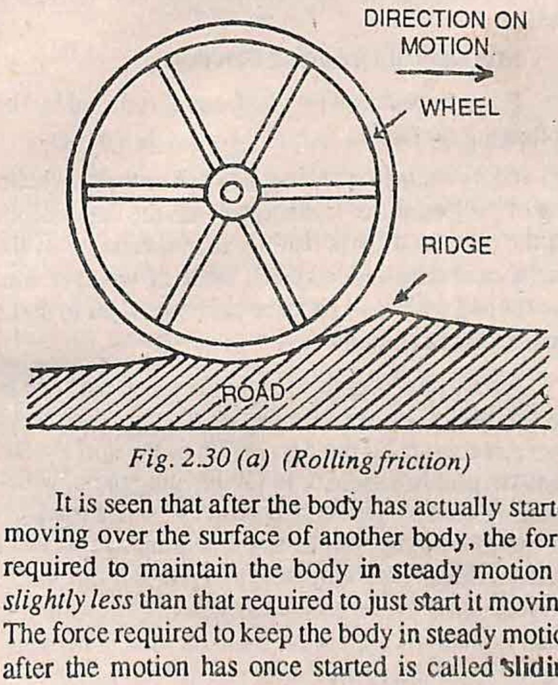


Fig. 2.30 (a) (Rolling friction)

It is seen that after the body has actually started moving over the surface of another body, the force required to maintain the body in steady motion is *slightly less* than that required to just start it moving. The force required to keep the body in steady motion after the motion has once started is called **sliding friction** or **dynamic friction** or **kinetic friction.** Thus the sliding friction is smaller than the limiting friction.

The difference between the limiting and sliding friction is further illustrated graphically in Fig. 2.29, where the force of friction is represented along OY and the applied force along OX. Before the motion begins, the force of friction is always equal to and changes at the same rate as the applied force. It is illustrated by the part OE of the curve. When the applied force becomes OF, the force of friction is maximum being equal to FE (limiting friction). As the applied force exceeds OF, the motion begins and the force of friction decreases to DN (sliding friction) which then remains constant.

Rolling Friction :

When a body rolls over surface of another body then the opposing force that comes into play is the **rolling friction.** In case of the rolling friction the area in contact of the moving body over the stationary one is either a point (in the case of a sphere) or a line (in the case of a cylinder) and it keeps on changing as the body rolls. The cause of the rolling friction can be either of the following two or both. (i) The stationary surface over which the other body rolls, is not perfectly rigid, so due to the weight of the rolling body or the weight acting on the rolling body the space just below the rolling body is depressed. When the rolling body moves it has to move up the ridge [Fig. 2.30 (a)] and energy is spent in doing it. (ii) The rolling body due to its own weight or the weight acting on it may become flat at the point of contact [Fig. 2.30 (b)].

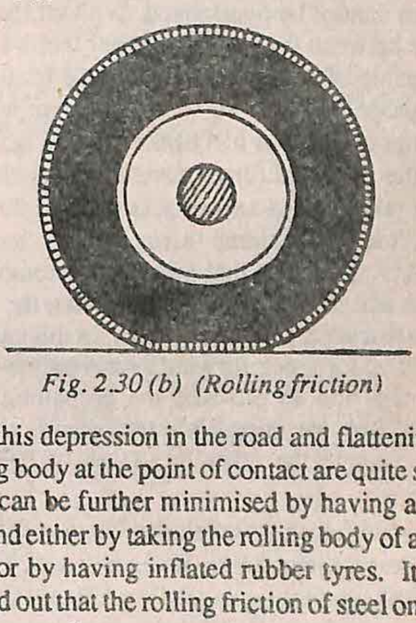


Fig. 2.30 (b) (Rolling friction)

But this depression in the road and flattening of the rolling body at the point of contact are quite small and they can be further minimised by having a hard surface and either by taking the rolling body of a hard material or by having inflated rubber tyres. It may be pointed out that the rolling friction of steel on steel is only about $\frac{1}{100}$th of the sliding friction between steel and steel. The rolling friction is very much less than the sliding friction that is why, wherever it is desired to have less fiction, the sliding of the body is changed into rolling. It is probably due to this consideration that even the primitive people started using circular wheels for the carriages. In the present times even the sliding between the shaft and the wheel is changed into rolling by using *ball-bearing* or *cylinder bearing* arrangements. These arrangements consist of two steel rings separated by small hard steel balls or rollers. The outer ring [Fig. 2.31] is connected to the wheel and the inner one to the shaft.

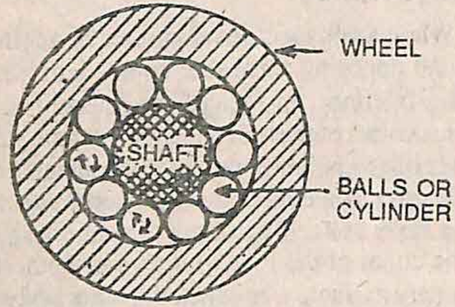


Fig. 2.31 Ball or Cylinder bearing.

Friction is Both A Necessity and an Evil :

That friction is so, is abundantly clear from our numerous experience in daily life.

Friction a Necessity :

Although friction appears as a force which opposes the efforts of man yet it has certain advantages which cannot be overlooked. Without the frictional force between the ground and our feet we should be incapable of walking, since it is the frictional force that propels us forward. In the action of walking, we attempt to slide our feet backwards along the ground and the frictional force prevents this sliding motion from taking place and so acts forward. In the same way, it is the frictional forces between the road and the driving wheels that propel an automobile. The motor acts to rotate the wheels so that the surface of the tyre tries to slide backwards. In this case also the frictional force acts forward to prevent the tyre from slipping, and so provides the propelling force. It would become impossible to transmit power from one point to the other by means of belts without friction.

Sand paper, grind-stones etc.,too depend upon friction for their action. In the absence of friction, it would be impossible to climb a tree, tie a knot or even fix a nail in the wall. Brick would not stand on brick, and buildings would tumble down like a house of cards. Indeed friction is so much of a necessity that we deliberately increase it for many purposes. For instance, we apply brakes to produce friction between them and the wheels of our cars or bicycles so as to stop their motion. Resin is applied to the belts used for the transmission of power to machines, to increase friction and avoid slipping. Thus we can multiply examples from our every day experiences to show that friction is a necessity in life and life would have become impossible without it.

Friction an evil :

And yet, in many other cases, the large value of friction is also a possible evil. For example, when friction occurs in-between the various parts of our machines, it makes their speed slower and their output is lowered and hence the efficiency of the machine is very much reduced. The work required to operate machines becomes large. Friction causes wear and tear of all the parts of a machine and thus increases the cost of running it. Moreover the energy wasted to overcome friction is converted into heat energy and causes an additional damage to the machine. We,therefore, use lubrication like oils etc., to reduce or minimise friction.

So it is rightly said that friction is a necessary evil.

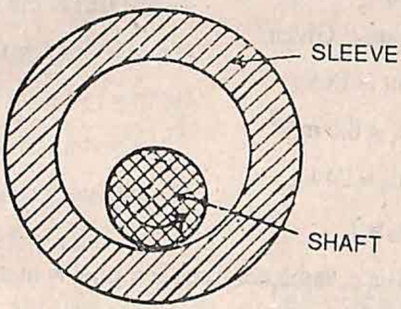
Methods of Reducing Friction

Friction between two surfaces is reduced by the following methods :

(i) *By Polishing* : Friction is due to the interlocking of projections of one surface into the depressions of the other and by polishing the unevenness of the surfaces is removed. Articles made of wood or iron are rubbed with sand paper or emery powder to make their surfaces smooth.

(ii) *By applying lubricants* : A lubricant such as an oil, grease or carbon powder is applied between two surfaces to fill the depression of the surface and thus friction is lessened. In all machine parts, which work in contact with each other, a constant supply of the lubricating oil has to be maintained. In order that the lubricants may not be squeezed out of the various parts of the machine, it is necessary that in heavy machinery *thick oil* must be used, whereas in light machinery like watches etc., *thin oil*. Our human body is a combinating of simple machines and nature has provided enough lubrication for those parts where sliding takes place, *e.g.*, in the joints, tendon sheaths and around the eye balls. Loss of lubrication leads to pain.

(iii) *By making the contact ball-bearing* : As rolling friction is much less than the sliding or dynamic friction, friction betwen two surfaces is reduced if one of the surfaces consists of small wheels or small rollers or steel shots. This is what is done in all wheel and axle arrangements in the machines [Fig. 2.52(a)]. You must have noticed that a wheel is always mounted on the axle and ball-bearing is a part of machine. In ball bearing, the axle rolls on balls without any sliding while the balls themselves roll. If the axle simply slides on the bottom of a sleeve,then it is called **sleeve bearing**[Fig 2.32] and there is sliding friction only. A ball bearing is preferred to sleeve bearing.



(Sleeve bearing)

Fig. 2.32

(iv) *By giving stream-line shape* : When a body moves in air or water with small speeds, it is the mechanical friction that matters most, for the friction due to the resistance of air or water is small. At high speeds, on the other hand, it is the air or water resistance that is predominant. That is why in case of sea ships, aeroplanes, railway engines, boats etc., the friction is reduced by giving them *stream-line shapes*. This explains why the shape of fast moving bodies are stream-lined.

(v) Friction can also be reduced by using *anti-friction* metals such as brass or bronze as it is found that friction between steel and steel is greater than the friction between steel and anti-friction metal.

Factors Affecting Friction :

The force of friction depends upon the following factors :

1. The force of friction is *directly proportional* to the *weight of the body* sliding over the surface.
2. The force of friction depends upon the *nature of the surfaces in contact*. The force of friction is *less* for *smooth surfaces*.
3. The force of friction is *independent of the area of the surface in contact so long as the weight of the body remains the same.*
4. Rolling friction is *less* than sliding friction.
5. The force of friction on a body *just before* it starts moving is always more than that when it is moving. The force of friction is *equal* to the applied force if the body slides *with a constant speed.*

SOLVED EXAMPLES

Example 1 :

A body of mass 0.5 kg is accelerated to $2 m/s^2$. What is the magnitude of the accelerating force ?

Solution :

Here, $m = 0.5$ kg

$a = 2 \text{ ms}^{-2}$

Accelerating force $= F = ?$

$F = ma$

$= 0.5 \times 2$

$= \mathbf{1 \; N}$

Example 2 :

Calculate the acceleration produced when a force of 30 N acts on a body of mass 300 g.

Solution :

Here, $F = 30$ N

$$m = 300 \, g = \frac{300}{1000} kg = 0.3 \, kg$$

Acceleration = a= ?

Since $F = ma$

$$\therefore a = \frac{F}{m} = \frac{30}{0.3} \text{ m/s}^2$$

$= \mathbf{100 \; m/s^2}$

Example 3 :

By how much does the momentum of a body of mass 3 kg change when its speed decreases from 40 m/s to 10 m/s.

Solution :

Here, $m = 3$ kg

Initial velocity $= u = 40$ m/s

Final velocity $= v = 10$ m/s

Initial momentum $= p_1 = mu$

$= 3 \times 40$

$= 120$ kg m/s

Final momentum $= p_2 = mv$

$= 3 \times 10$

$= 30$ kg m/s

∴ decrease in momentum

$= p_1 - p_2$

$= 120 - 30$

= 90 kg m/s

Example 4 :

A man in a circus show jumps from a height of 10 m and is caught by a net spread below him. The net sages down 2 m due to his impact. Find out the average force exerted by the net on the man to stop his fall. Take the mass of the man to be 60 kg and consider the value of acceleration during his free fall as 10 m/s^2.

Solution :

Here, $u = 0$

$a = g = 10$ m/s^2

$s = 10$ m

Let v be the velocity with which the man strikes the net.

∴ $v^2 - u^2 = 2as$

or $v^2 - 0 = 2 \times 10 \times 10$

or $v^2 = 200$

or $v = 10\sqrt{2}$ m/s

Let F be the average force exerted by the net on the man to stop his fall. For this journey,

Initial velocity $= 10\sqrt{2}$ m/s

Final velocity $= 0$

Retardation $= a = ?$

Distance covered $= 2$ m

∴ $v^2 - u^2 = 2as$

∴ $(0)^2 -- (10\sqrt{2})^2 = 2a \times 2$

or Retardation $= a = -50$ m/s^2

Since $m = 60$ kg

∴ Average Force $= m a$

$= 60 \times 50$

= 3000 N

Example 5 :

If a net force gives a 18 kg mass an acceleration of 8.0 ms^{-2}, what acceleration would the same net force give a 24 kg mass ?

Solution : Given,

$m_1 = 18$ kg

$a_1 = 8.0$ m/s^2

$m_2 = 24$ kg

$a_2 = ?$

Since, same net force $F = m_1a_1 = m_2a_2$

therefore,

$$a_2 = \frac{m_1 \, a_1}{m_2}$$

$$= \frac{18 \times 8}{24} \text{ m/s}^2$$

$$= 6.0 \text{ m/s}^2$$

Example 6 :

Determine the magnitude of a net force on a 20.0 kg block if it accelerates uniformly from 2.50 m/s to 5.80 m/s in 3.00s.

Solution :

Initial velocity $= u =$ 2.50 m/s

Final velocity $= v =$ 5.80 m/s

Time taken $= t =$ 3.00 s

Mass of the block $= m = 20.0$ kg

Net force $= F = ?$

Since, $F = ma$

and $a = \frac{v - u}{t}$

$$\therefore\ F = \frac{m(v-u)}{t}$$

$$= \frac{20.0\,[5.80 - 2.50]}{3.00}\ \text{N}$$

$$= 22.0\ \text{N}$$

Example 7:

Determine (i) the acceleration and (ii) the distance travelled in 6.00 s when a 7500 N net force accelerates a 1500 kg car uniformly from rest.

Solution :

Net force = F = 7500 N

mass = m = 1500 kg

Initial velocity = u = 0

Time taken = t = 6.00 s

Acceleration = a = ?

Distance travelled = S = ?

Since F = ma

(i) $\therefore$ Acceleration $a = \frac{F}{m} = \frac{7500}{1500} = \boxed{5.0\ \text{m/s}^2}$

(ii) As $S = ut + \frac{1}{2}at^2$

$$\therefore\ S = 0 + \frac{1}{2} \times 5 \times 36\ \text{m}$$

$$\boxed{= 90\ \text{m}}$$

Example 8 :

A stationary football weighing 0.5 kg acquires a speed of 15 m/s when kicked by a player. What is the impulse imparted to the football ?

Solution :

Here, mass = m = 0.5 kg

Initial velocity = u = 0

Final velocity = v = 15 m/s

Impulse = ?

Now, Impulse = Ft = m (v–u)

$$= 0.5\,[15-0]$$

$$\boxed{= 7.5\ \text{Ns}}$$

Example 9:

A man throws a ball weighing 0.5 kg vertically upwards with a speed of 10 m/s. What will be its initial momentum ? What would be its momentum at the highest point of its flight ?

Solution :

Here, mass of the ball (m) = 0.5 kg

Initial speed = u = 10 m/s

Initial momentum = mu = 0.5 × 10

$$= \boxed{5\ \text{kgm/s}}$$

At the highest point velocity of the ball is zero as it rises up with *uniform retardation* due to gravity.

$\therefore$ Momentum of the ball at the highest point = mass x velocity

$$= 5 \times 0$$

$$= 0$$

Example 10 :

A 0.250 kg ball is thrown with an initial speed of 20.0 m/s to a batter, who hits it back along its original path with a speed of 30.0 m/s. If the duration of the impact was 10.0 ms, what was the magnitude of the average force on the ball ?

Solution :

The ball changes direction after impact ; therefore, if the final direction of the ball's motion is taken as *positive*, the final velocity v = 30 m/s, and the initial velocity u = –20.0 m/s,

m = 0.250 kg,

t = 10.0 ms = 0.0100 S

Since, F×t = m (v—u)

$$\therefore\ F = \frac{m(v-u)}{t}$$

$$= \frac{0.250\,[30 - (-20)]}{0.0100}\ \text{N}$$

$$= \boxed{1250\ \text{N}}$$

Example 11 :

Determine the momentum of a 1250 kg car that travels due West at 22.5 m/s.

Solution :

Mass of the car = m = 1250 kg

Velocity of the car = $\vec{v}$ = 22.5 m/s West

Momentum = $\vec{p}$ = ?

Since $\vec{p} = m\vec{v}$

$\therefore \quad \vec{p}$ = 1250 × 22.5 N.s. West

$\boxed{= 2.80 \times 10^4 \text{ N.s West}}$

Example 12 :

The distance-time table of an object initially at rest is as follows :

Time (Seconds)	0	1	2	3	4	5	6	7	8	9	10
Distance (metre)	0	4	16	36	64	100	144	196	256	324	400

(a) What conclusion can we draw about the acceleration ? Is it constant, increasing, decreasing or zero ?

(b) What do you infer about the forces acting on the object ?

(c) Plot the distance-time graph of the motion.

Solution :

(a) It is clear from the distance-time table that the distance covered by the object in each successive second is increasing and hence its speed is not constant but is increasing with time. In other words the object is being *accelerated i.e.*, the acceleration is not zero.

To find out whether the acceleration is constant or not, let us examine the equation of motion

$$S = ut + \frac{1}{2}at^2$$

where S is the distance travelled by the object in time

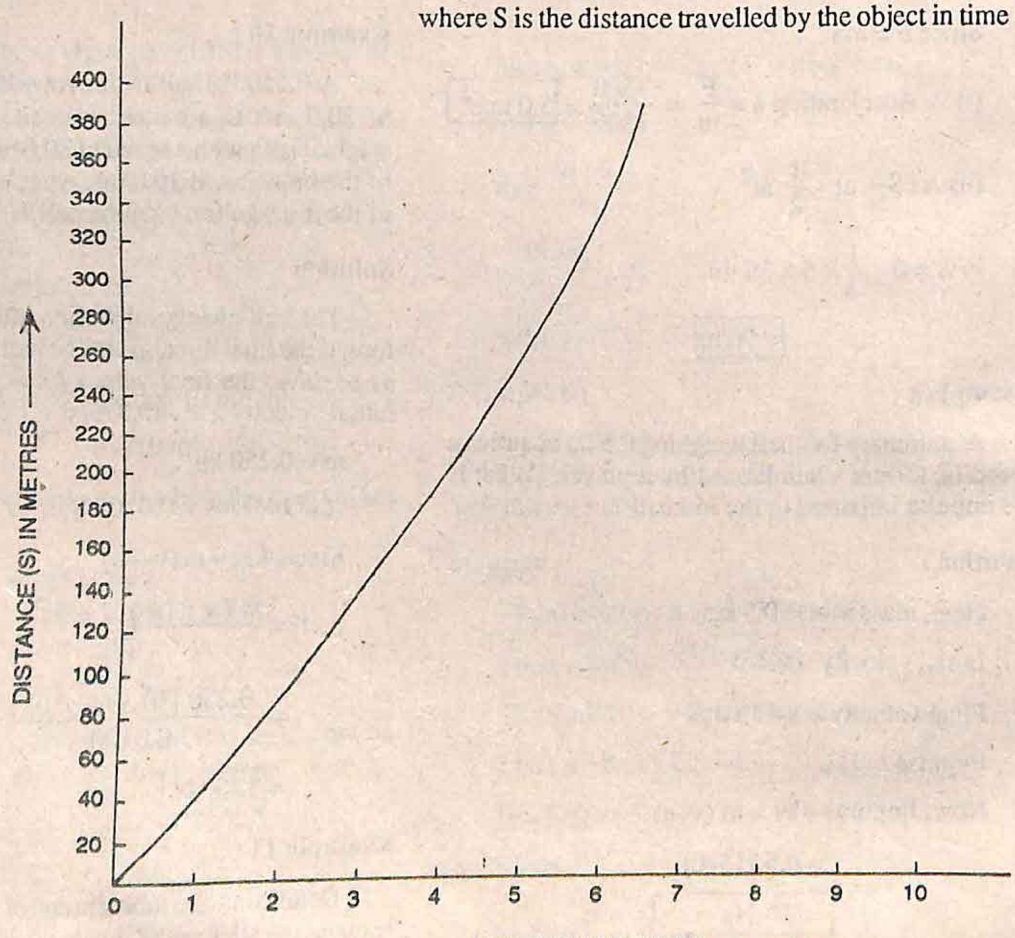


Fig. 2.33

t seconds if the motion starts at time $t = 0$, u is the initial velocity and a is the *uniform acceleration* of the object. Remember this equation is true only for uniformly accelerated motion *i.e., a is constant.*

If the object starts from rest, that is, its initial velocity $u = 0$ then the above equation of motion becomes

$$S = \frac{1}{2} at^2$$

Since a is constant, so

$$\boxed{S \propto t^2}$$

Thus, we find that, for a uniformly accelerated motion, the distance (S) travelled in time (t) is directly proportional to the time squared.

If we carefully examine the given distance-time table then we find that

$$S \propto t^2$$

Hence, we can conclude that the object is moving with *constant acceleration.*

We can even find the magnitude of the acceleration by putting $S = 4$ m when $t = 1$ second from the above table in the equation of motion

$$S = \frac{1}{2} at^2 \ (\because u = 0)$$

$$4 = \frac{1}{2} a (1)^2$$

or $$\boxed{a = 8 \text{ m/s}^2}$$

Thus the object has a constant acceleration of 8 ms^{-2}.

(b) Since the object has a constant acceleration, there must be a *constant unbalanced force* acting on it.

(c) To draw the distance-time graph of the motion of this object, we must choose convenient scales for distance and time and plot distance versus time as shown in Fig. 2.33.

The shape of the curve that we obtain is called a **parabola.** The distance-time graph of any uniformly accelerated motion is a parabola. In fact it was Galileo who first deduced that if an object travels with uniform acceleration, the distance travelled varies as the square of the time taken. Galileo did not have good clocks to measure time accurately. It is said that he used his pulse to measure the time.

Example 13 :

Two blocks made of different metals *identical* in shape and size are acted upon by *equal* forces which cause them to *slide* on a horizontal surface. The acceleration of the second block is found to be 3 times that of the first, what is the ratio of the mass of the second to the first ?

Solution :

As the blocks are identical in shape and size so their volumes are equal. Again as the blocks are made of different metals so their densities are different and hence the blocks have *different weights.*

Now, the force of friction experienced by a body when it slides on a horizontal surface depends on its weight as well as on the area of its surface in contact with the horizontal surface. Since the surface area in contact with the horizontal surface for both the blocks is the *same* as they are identical in shape and size and as their weights are different so both the blocks experience *different frictional forces.*

Let f_1 and f_2 be the force of friction experienced by the first and the second block respectively. Let F_1 and F_2 be the external force exerted on the first and the second block respectively.

Therefore, the force which causes sliding of the first block = $(F_1 - f_1)$ as friction opposes motion. Similarly, the force which causes sliding of the second block = $(F_2 - f_2)$.

It is given that

$$(F_1 - f_1) = (F_2 - f_2)$$

If m_1 is the mass of the first block and a_1 is the acceleration produced in it ; m_2 is the mass of the second block and a_2 is the acceleration produced in it then

$$(F_1 - f_1) = m_1 a_1$$

and $$(F_2 - f_2) = m_2 a_2$$

Hence, $$m_1 a_1 = m_2 a_2$$

or $$\frac{m_1}{m_2} = \frac{a_2}{a_1}.$$

But $$\frac{a_2}{a_1} = 3 \text{ (Given)}$$

Thus, $$\frac{m_1}{m_2} = 3$$

or $\boxed{m_1 = 3\ m_2}$

Example 14 :

A truck starts from rest and rolls down a hill with constant acceleration. It travels a distance of 400 m in 20 s. Find its acceleration. Find the force acting on it if its mass is 7 metric tonnes (1 metric tonne = 1000 kg).

Solution :

Given,

Initial velocity of the truck = $u = 0$

Distance travelled = $S = 400$ m

Time taken = $t = 20$ s

Acceleration = a = ?

Mass of the truck = m = 7 metric tonnes

= 7000 kg

Force (F) = ?

Now, $S = ut + \frac{1}{2}\ at^2$

$\therefore\ 400 = 0 \times 20 + \frac{1}{2} \times a \times (20)^2$

or $a = \boxed{2 m/s^2}$

Again, $F = ma$

$F = 7000 \times 2$ N

$\boxed{= 14000\ N}$

Example 15:

A force of 5 newton gives a mass m_1 an acceleration of 8 m/s^2 and a mass m_2 an acceleration of 24 m/s^2. What acceleration would it give if both the masses are tied together ?

Soltuion :

For mass m1

Force = F = 5 N

Acceleration = $a_1 = 8\ ms^{-2}$

Mass m_1 = ?

Since $F = m_1\ a_1$

$\therefore\ m_1 = \frac{F}{a_1} = \frac{5}{8}$ kg

For mass m2

Force = F = 5N

Acceleration = $a_2 = 24\ ms^{-2}$

Mass m_2 = ?

As $F = m_2\ a_2$

$\therefore\ m_2 = \frac{F}{a_2} = \frac{5}{24}$ kg

If the two masses are tied together then their total mass $m = (m_1 + m_2)$

$= \left(\frac{5}{8} + \frac{5}{24}\right)$kg

$= \frac{5}{6}$ kg

Acceleration = $\frac{\text{Force}}{\text{Mass}} = \frac{5}{5/6} = 6\ m/s^2$

Example 16 :

A certain force exerted for 1.2s on a moving object increases its speed from 1.8 m/s to 4.2 ms^{-1}. How much will the speed of the object change if the same force is later applied for 2s ?

Solution :

Given,

Initial velocity = $u = 1.8$ m/s

Final velocity = $v = 4.2$ m/s

Time taken (t) = 1.2s

Since, acceleration (a)

$= \frac{v-u}{t} = \frac{\text{Change in speed}}{\text{Time}}$

$\therefore\ a = \frac{4.2 - 1.8}{1.2}\ m/s^2$

$= \boxed{2\ m/s^2}$

Since the same force is applied to the same object for t=2 seconds, the acceleration produced must be the same *i.e.*, $a = 2\ m/s^2$

Hence, change in speed

in 2 seconds $= a \times t$

$= 2 \times 2 = \boxed{4\ m/s}$

SUMMARY

1. A *force* is anything which causes a body to start moving when it is at rest, or stop it when it is moving or deflect it once it is moving. In other words *it changes the velocity of an object.*

   Force is a *vector* quantity. It is measured in *newton* (N).

   One newton is defined as that force which, when applied to a mass of 1 kg, produces an acceleration of $1 m/s^2$.

2. Forces which just balance and produce no motion are called *balanced forces* and they are said to be in *equilibrium.* The resultant of such forces is zero. Equilibrium means *no acceleration. Unbalanced forces* are those forces which produce change in the state of motion of a body.

3. *Inertia* is the tendency of a body to stay at rest or stay moving. Force overcomes the inertia of the body.

   Mass of a body is the quantity of matter in a body ad mass is a *measure* of inertia (resistance to change in motion).

4. *Newton's First Law of Motion :*

   Every body continues in its state of rest or of uniform motion along the same direction unless it is acted upon by an unbalanced force.

   It is also called law of inertia and this law gives us the definition of force.

5. *Newton's Second Law of Motion :*

   "If an unbalanced force acts upon a body that force will produce an acceleration of the body in the direction of the force. The magnitude of the acceleration is directly proportional to the magnitude of the unbalanced force and is inversely proportional to the mass of the body."

   $$\vec{F} = m\vec{a}$$

   This law may also be defined as:

   "The rate of change of momentum of a body is equal to the unbalanced force acting on it."

   $$F = \frac{(m\vec{v} - m\vec{u})}{t} = \frac{\overrightarrow{p2} - \overrightarrow{p1}}{t}$$

   Newton's second law of motion gives us the *measurement of force.*

   Force (N) = Mass (kg) × Acceleration (m/s^2)

6. *Newton's Third Law of Motion :*

   "To every action there is an equal and opposite reaction."

7. *Momentum* is the total quantity of motion of a body and is measured by the product of mass and velocity

   $$\vec{p} = m\vec{v}$$

   Its unit is kg m/s or newton-second and it is a *vector* quantity.

   Impulse = $Ft = mv - mu = \overrightarrow{p2} - \overrightarrow{p1}$

8. Its unit is newton-second (Ns) or kg m/s.

9. *Force of friction* is that force which is brought into play when one body tends to move over another and which always opposes motion.

   Force of friction acts only between bodies in contact. The *unevenness* or *roughness* of the surfaces is the major factor which contributes to the force of friction. The maximum force of friction that is called into play when one body just begins to move over the surface of another body is called *limiting friction.*

10. The *effective force* acting on the object is the difference in the magnitude of the applied force and the limiting force of friction.

    Friction continues to act on the body even when it is in motion. When the applied force is withdrawn, the force of friction continues to act and ultimately brings the body to rest.

11. The force of friction depends upon various factors:

    (i) If the *normal* or perpendicular force pressing the two surfaces together is doubled, the limiting friction is also doubled.

    (ii) If the force pressing the surfaces together is kept constant, but the area the surfaces in contact is doubled, the limiting friction is unchanged.

(iii) Smooth surfaces like glass and polished metal have very little friction whereas rough surfaces like sawn wood or sand paper have a lot of friction.

(iv) Rolling friction is *less* than sliding friction.

(v) Force of friction is a *self-adjusting* force.

QUESTIONS

[A] Objective Type Questions :

1. Which of the following is a unit of force?

(a) metre (b) newton

(c) kilogram-second (d) metre/second

2. As the mass of the contents of a box is increased, the force required to give all of it a constant acceleration.

(a) decreases (b) increases

(c) remains the same.

3. A force of 120 N acts on a mass of 60 kg. If no other force acts on the object, the acceleration, in ms^{-2}, is

(a) 18 (b) 1800

(c) 0.50 (d) 2.0

4. A 4 kg mass moves with a velocity of 10 ms^{-1} for 5 seconds. Its momentum is.......

5. An automobile weighs 3200 kg. The net force needed to give it an acceleration of 8 ms^{-2} is..........

6. A man fires in rifle. The bullet from this gun has a momentum of 20 kg ms^{-1}. The magnitude of the momentum of the rifle under these conditions is, in kg ms^{-1},

(a) 20 (b) less than 20

(c) more than 20

7. In an object with a mass of 6 kg experiences a force of 8 N for 5 seconds, its change in momentum, in kg ms^{-1}, is

(a) 30 (b) 40

(c) 48 (d) 480

8. The product of a force and the time interval during which it acts is called.........

9. As a constant unbalanced force acts on an object, its acceleration............

10. As the force exerted by one object on another increases, the force exerted by the second object on the first...........

11. If two parallel forces of 20N and 10N respectively produce no acceleration (*i.e.,* are in equilibrium) with a force of 30N, the net force acting on the object is............

12. The maximum force of friction is called..........friction.

13. What force is necessary to keep a book sliding with constant velocity across a desk if there is a frictional force of 9 N opposing the motion ?

14. What is produced when a net force acts upon a body?

15. Complete the following statements :

(i) When an object is free to move and a force is applied to it, it will............

(ii) When an object is free to move and two equal and opposite forces are applied to it, it will............

(iii) If an object is moving and a force is applied to it in the opposite direction, it will ....

(iv) Two conditions concerning forces which must apply to a body moving with constant velocity are

(a) that..........., or

(b) that..........

(v) When an object is free to move and a number of different forces are applied to it in different directions it will move provided that..........

16. The action and reaction forces referred to in Newton's third law of motion

(a) must act on different objects

(b) must act on the same object

(c) need not be equal in magnitude but must have the same direction.

17. If P and Q are two stones with masses 10 kg and 40 kg respectively, then

(i) P has more inertia than Q

(ii) Q has more inertia than P

(iii) Pand Q have the same inertia

(iv) None of the two has inertia.

18. A force acts on an object which is free to move. If we know the magnitude of the force and the mass of the object, Newton's second law of motion enables us to determine the object's

(a) speed

(b) weight

(c) acceleration

(d) position

19. When an object undergoes acceleration

(i) its velocity always increases

(ii) its speed always increases

(iii) a force always acts on it

(iv) its momentum remains constant.

20. When a net force acts on a car, it will be accelerated in the direction of the force with an acceleration proportional to

(i) the velocity of the car

(ii) the mass of the car

(iii) the inertia of the car

(iv) the force on the car.

21. When a force of 10 newton acts on a body of mass 2 kg that is able to move freely, the body moves with a

(i) speed of 5 ms^{-1}

(ii) acceleration of 5 ms^{-2}

(iii) acceleration of 0.2 ms^{-2}

(iv) speed of 20 ms^{-1}

(v) acceleration of 20 ms^{-2}

(Choose the right answer)

[B] Very Short Answer Type Questions :

1. If an object is to accelerate, what must act on the object ?

2. According to Newton's first law of motion, how large a force is acting on an object which moves with constant velocity ?

[Hints : Any force acting on it in one direction, must be balanced by an equal force in the opposite direction].

3. To what is the acceleration of an object proportional ?
4. How are mass and inertia related ?
5. Define momentum.
6. Is momentum a scalar quantity or a vector quantity ?
7. What is imuplse ?
8. In what direction can friction act on an object which is not moving ?
9. On what does the friction between two solid surfaces depend ?
10. Give S.I. unit of (i) force, (ii) momentum, (iii) impulse.
11. Name the physical quantity that measures the inertia of a body. Give its S.I. Unit.
12. Is it true that action and reaction act on the same body ?
13. Name the physical quantity that is directly proportional to rate of change of momentum.
14. Which has more inertia : a loaded bus or an unloaded bus ?
15. Friction always opposes motion–is it false or true ?
16. How must force is needed to move a body of mass 2 kg with an acceleration of 1 m/s^2?

[C] Short Answer Type and Essay Type Questions :

1. Define force. Mention and define the units in which force is measured in the SI system and in the C.G.S. system.
2. Distinguish between force and mass.
   When a junked car is crushed into a compact tube, does its mass change ?
3. Define : newton ; dyne. How is newton related to dyne (numerically) ?
4. Define : Inertia ; momentum ; impulse ; action; reaction ; friction.
5. State Newton's laws of motion. Give two examples in each case.
6. State Newton's first law of motion. Explain how does it give the definition of force.
7. Why Newton's first law of motion is also called the law of inertia ?
8. What do you understand by the term inertia ? Distinguish between inertia of rest and inertia of motion. Give two examples in each case.
9. State Newton's second law of motion and explain how does it give the measurement of force?
   If an object has no acceleration, can we conclude that no forces are exerted on it?
10. Derive the relation
    $F = ma$
    where F is the force acting on a body of mass m and a is the acceleration produced in the body.
11. State Newton's third law of motion. Give two examples to illustrate this law.
12. "Newton's second law of motion is the only law of motion." Explain.
13. Define momentum. Give its SI unit. How is it related to force?
14. Define impulse. Give its SI unit. How is it related to (i) force, (ii) momentum ?
15. Define friction. What is the difference between static friction and sliding friction ? Which of them is greater ?
16. Why are the moving parts of an engine oiled ?
17. Explain the statement : "Friction is a necessary evil".

18. How will you increase or decrease friction ?

19. What is rolling friction ? What is sliding friction ?
Explain the importance of a wheel in everyday life.

20. What is force of friction? Enumerate the factors (or parameters) that affect the force of friction between two surfaces when one surface slides over the other.

21. A heavy stone is lying on the road. A boy applies a force of 150 N to pull it, but fails. Then a young man pulls it by a force 500 N, but fails. Then an athlete applies a force of 800N and is able to pull it.
(a) What force does prevent it from moving in the first two cases?
(b) What conclusions can you draw about the force from these two observations ?

22. Explain how a quantitative definition of force is given by Newton's second law of motion. Discuss what is implied by saying that the acceleration of a body gradually decrease to zero.

23. Indicate the action and reaction in each of the following cases:
(i) A stone suspended with a thread.
(ii) A man standing on the ground.

24. Which physical principle is involved in the working of a jet plane?

25. Pull your hand towards you across the surface of a table. Which way does friction act : up, down towards you, away from you, sideways ?

26. Push against a wall :
(a) As there is no movement, what does this indicate about the forces ?
(b) If the wall was to push back with a greater force, what would happen ?
(c) If the wall was to push back with a less force, what would happen ?
(d) What could be said about the balance of forces in the situations described in (b) and (c) ?

27. (a) If an object has large inertia, is it difficult or easy to set it in motion, or to stop it once started ?
(b) Will an object have a different inertia in the weightlessness of space ?
(c) Explain why the middle book of a pile of books can be pulled out quickly without the top books falling over or coming with it?
(d) Two identical trolleys each of one kilogram mass are attached to clamp stands by identical springs which have been stretched by the *same* amount. One of the trolleys has a two kilogram mass placed on it. Which trolley when released, will have the greater acceleration ? Explain your answer using the word inertia.
(e) A load of one kilogram is hung on a piece of strong thread and an extra piece of thread attached to the base of the load. Why is it that a *sharp* pull downwards on the lower piece of thread will cause a break to occur below the load while a *slow* pull will snap the thread above the weight ?
(f) A heavy box is lying on the floor of a room. What are the forces acting on it? If one tries to push the box and it does not move, does this imply a violation of Newton's second law of motion ? Explain.
(A.I.S.S. 1986)
(g) Consider hitting a cricket ball with a bat. If we call the force on the bat against the ball the *action* force, identify the *reaction* force.

28. With practice, and many broken dishes, it is possible to jerk a tablecloth from a table without significantly disturbing the dishes. Explain how this trick works.

29. When a bus accelerates, the passengers feel pushed backward into their seats, and when a bus turns a corner, they tend to feel pushed to one side. Explain these effects.

30. Can the mass of a material object ever be zero?

31. Explain, in terms of Newton's laws of motion and friction, why it is difficult to walk on ice.

32. Why are lubricants and bearings used in machinery?

33. In space, astronauts are able to move with the aid of small rockets. Explain the principles involved.

34. If you are on a frictionless surface, how could you move?

35. Seat belts normally reduce the possibility of injury during an automobile accident. Explain why.

36. Once a spaceship has cleared the gravitational pull of a celestial body, it will continue in a straight line through space without the use of additional rocket power. Explain why this is possible.

37. Why are the passengers jerked forward when the moving car suddenly stops?

38. Why does your toe hurt when you kick a stone?

39. Will you stop a speeding cricket ball suddenly with your palm flat or will you stop it gradully pulling your arm back with the ball ? Explain.

40. What kind of path would the planets follow if suddenly no force acted on them ?

41. If the mass of a sliding block is *tripled* while a constant net force is applied, by how much does the acceleration decrease?

42. Why do action and reaction pairs of forces never cancel each other ?

PROBLEMS

1. A force changes the velocity of a body of mass 10 kg from 5 ms^{-1} to 20 ms^{-1} in 2 seconds, find

(i) the initial momentum of the body (ii) the final momentum of the body

(iii) the change in momentum of the body (iv) the force acting on the body.

[**Ans.** (i) 50 kg m/s (ii) 200 kg m/s (iii) 150 kg m/s (iv) 75 N]

2. Find the force acting when a 10 kg mass accelerates at 4 m/s^2. [Ans : 40 N]

3. What is the magnitude of the force which when acts on a mass of 1.5 kg gives it a velocity of 5 m/s in one minute ?

[Ans : 0.125 N]

4. What is the momentum of a beam of 10^{12} electrons travelling together with a speed of 10^6 m/s ? The mass of each electron being 9×10^{-31} kg.

[Ans : 9×10^{-13} kg m/s]

5. A force of 10N acts on a body of mass 2 kg. Find the acceleration produced in the body.

[Ans : 5 ms^{-2}]

6. A gun of mass 10 tonnes fires a shot of 50 kg with a velocity of 250 m/s. Find the velocity of the recoil of the gun and compare the momenta.

[Ans : 1.25 ms^{-1}; equal]

7. A stationary ball weighing 0.25 kg acquires a speed of 10 m/s when hit by a hockey stick. What is the impulse imparted to the ball ?

[Ans : 2.5 Ns]

8. A motor–car of mass 2000 kg is moving with a velocity of 36 km/h. By the application of brakes it is brought to rest in a distance of 40 m. Find the average force resisting the motion.

[Ans : 2500 N]

9. A driver accelerates his car first at the rate of 1.8 m/s^2 and then at the rate of 1.2 m/s^2. Calculate the ratio of the force exerted by the engine in the two cases.

[Ans : 3:2]

10. A plastic ball having a mass of 1 kg and a velocity of 8ms^{-1} southward collides with a 2 kg ball travelling along the same path with a velocity of 3 ms^{-1} southward. If the velocity of the 2 kg ball after impact is 4.5 ms^{-1} southward, what is the velocity of the 1 kg ball?

[Ans : 5m/s southward]

11. A target of mass 0.4 kg moving with a horizontal speed of 10 ms^{-1} is hit by a bullet of mass 0.01 kg moving in the opposite direction. If both the bullet and the target come to rest after the collision, calculate the velocity of the bullet at the time of striking the target.

[Ans : 400ms^{-1}]

12. A body of mass 2 kg is at rest. What should be the magnitude of force which will make the body move with a velocity of 30 ms^{-1} at the end of 1s?

[Ans : 50 N]

13. Two bodies of masses 1 kg and 2 kg respectively move in opposite direction with a speed of 5 m/s and collide. What is the total momentum before collision?

[Ans : 5 kg ms^{-1} in the direction in which a body of mass 2kg moves]

14. A 36.0 g ball is hit off a bat with an initial speed of 75.0 m/s. What magnitude impulse was it given ?

[Ans : 2.7 N.s.]

15. Determine the magnitude of the linear momentum of an 225 g hockey puck travelling at 162 km/h.

[Ans : 10.1 kg m/s]

16. What is the mass of a body which is acted upon by a 12 N net force and which produces in it an acceleration of 0.80 m/s^2?

[Ans : 15 kg]

17. The distance-time table of an object initially at rest is as follows:

Time (t) in seconds	0	1	2	3	4	5	6
Distance (s) in metres	0	1	4	9	16	25	36

(a) What conclusion can you draw about the accelertion ? Is it constant, increasing, decreasing or zero?

(b) What do you infer about the forces acting on the object, if any?

(c) Plot the distance-time graph of the motion.

[Ans : The object has a *constant* acceleration of 2 m/s^2]

18. The distance-time graph of an object, initially at rest, is as follows:

Time (t) in seconds	0	1	2	3	4	5	6
Distance (s) in metres	0	1	8	27	64	125	216

(a) What conclusion can you draw about the acceleration ? Is it constant, increasing, decreasing or zero?

(b) What do you infer about the forces acting on the object ?

[Ans : (a) Acceleration is increasing with time

(b) Net force acting is increasing with time]

19. A force of 300 N applied to a mass produces an acceleration of 5ms^{-2}. Find (i) its mass, (ii) its velocity at the end of 10s and (iii) the distance it moves in 10s.

[Ans : (i) 60 kg (ii) 50 m/s (iii) 250 m]

CHAPTER — 3

GRAVITATION

LEARNING OBJECTIVES

At the completion of this Chapter, you should be able to grasp:

1. The meaning of gravitation; gravity; free fall; acceleration due to gravity of a planet.
2. The law of gravitation and why is it called the *universal law.*
3. The meaning of the *universal* gravitational constant G; its magnitude and SI units.
4. Variation of g with altitude, latitude and depth.
5. The meaning of a projectile and the nature of its path (trajectory).
6. In the absence of air, all bodies fall at the same rate.
7. The equations of motion of a body under gravity.
8. Newton's third law of motion and gravitation.
9. The meaning of mass with gravity.
10. Difference between (i) weight and mass; (ii) inertial mass and gravitational mass.
11. The concept of *weightlessness* in space.
12. The meaning of a satellite; the difference between natural satellites and an artificial satellite.

Moon is the natural satellite of earth and it is constantly falling.

3.1 INTRODUCTION

Force is the push or pull of one body on another causing an acceleration. In general, an *unbalanced force F* acting on a mass m causes the mass to move with an acceleration a where $F = ma$. Thus, if we find an accelerating body, it is certain that some force must be acting on it.

When an object is released from a short distance above the earth it accelerates to the ground with a constant acceleration known as the *acceleration of free fall* and the force responsible for this acceleration is called the *gravitational force* which is one of the various kinds of forces that we come across in every day life *e.g.* Elastic forces; Cohesive forces; Impact forces; Electric and Magnetic forces; Nuclear forces; Muscular forces etc. In this Chapter, we will discuss the gravitational force.

3.2 FORCE OF GRAVITATION

If you lift a brick at some height above the floor and let go of it, it falls to the ground. What causes this to happen? How did it accelerate? Bricks do not move sideways without being pushed or pulled and they do not move upwards unless they are thrown or something is pulling them. This means that if anything moves downwards there must be some force pushing it or pulling it towards the ground. You can feel this force if you hold anything in your hand or try to lift anything off the floor. The first person to discover why things fall to the ground was Sir Isaac Newton. It is said that one day he was sitting in his mother's orchard when he saw an apple fall from a tree. This started him thinking why such a thing should happen. His explanation was that the earth and the apple pull each other together. The earth attracts the apple and

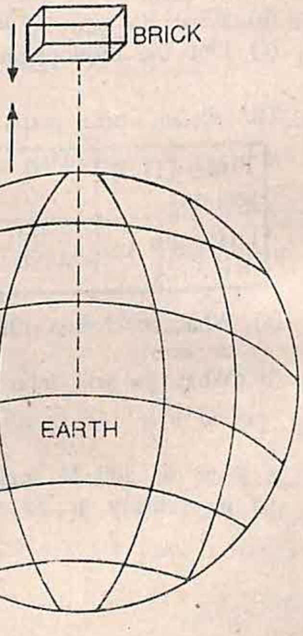


Fig. 3.1

the apple attracts the earth. The earth is very large and is not affected by the pull of the apple. The apple, being much smaller, is pulled down towards the earth. It required the genius of Newton to realise that this attraction is only a particular case of a universal attraction between any two bodies situated anywhere in the universe. *Every particle of matter in this universe attracts every other particle with a certain force in the direction of the line joining their centres.* **This force of universal attraction between any two particles of bodies is known as gravitation or force of gravitation. It takes place over unlimited distances and is independent of the materials of which the bodies are made.**

This force of attraction is very small between bodies of moderate size but, when, one or both of the bodies is sufficiently large, the force becomes evident. It is the force of attraction which the sun exerts on the earth that causes the earth to describe an orbit around the sun. The moon and the other planets also are held in space in their orbits on account of a similar force. The tides, which are risings and fallings of level of water on the shore of an ocean, are due to the force of attraction that the moon and the sun exerts on the water on the surface of the earth. Near the surface of the earth, this force is responsible for holding our atmosphere, for the flow of rivers, for holding us firmly on to the ground etc. The force of gravitation is one of the fundamental forces in nature.

3.3 NEWTON'S LAW OF UNIVERSAL GRAVITATION

Sir Isaac Newton established a law about the force of attraction between any two particles in the universe and the law is known as **Newton's Law of Gravitation.** It states that :

> *"Every body in this universe attracts every other body with a force which varies directly as the product of their masses and inversely as the square of the distance between their centres. The direction of force is along the line joining the two masses."*

Mathematically expressing the law, we can write that

$$F \propto \frac{m_1 m_2}{r^2}$$

where F is the force of attraction between the two bodies of masses m_1 and m_2 and r is the distance between them.

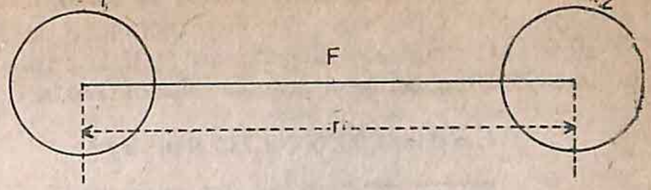


Fig. 3.2

The gravitational force *G* can be written in the form of an equation as

$$\boxed{F = \frac{G m_1 m_2}{r^2}} \quad \dots (1)$$

where G is a constant of proportionality and is known as **Universal Gravitational Constant.**

It has been found that the value of G in equation (1) does not depend upon the values of m_1, m_2 or r. It also does not depend upon who measures F and when or where it is measured. The constant G will remain the same for any two objects in this universe. This means that, if we measure the force of attraction between the sun and the earth or between the stone and the earth or between two distant stars, the ratio

$$\frac{F}{\left(\frac{m_1 m_2}{r^2}\right)}$$

which is equal to the constant *G*, is the same for any of these pairs of objects. *Such a constant quantity whose value remains the same anywhere in the universe is called a* **Universal Constant.** Universal constants are very special numbers. This particular constant G is *extremely small.*

The *Unit* of G depends upon the units you choose for force *F*, masses m_1 and m_2 and the distance *r*. In the SI system, the force *F* is expressed in newton (N), mass m in *kilogram* (kg) and the distance r in *metre* (m). The units of G in S I system will, therefore, be

$$\frac{\text{newton}}{(\text{kg})^2/(\text{metre})^2} = \frac{(\text{newton})\,(\text{metre})^2}{(\text{kg})^2}$$

$$= \frac{\text{Nm}^2}{\text{kg}^2} = \text{Nm}^2\ \text{kg}^{-2}$$

Scientists have performed very careful experiments to measure the *value* of G in a laboratory. To measure the value of G, we have to measure the force of attraction (*F*) between two known masses m_1 and m_2 separated by a known distance (r). The most famous experiment* to measure G accurately was performed by *C. V.* Boys in 1895. His experiment gave the value of *G* to be

$$G = 0{\cdot}000000000066734 \text{ N m}^2 \text{ kg}^{-2}$$

$$\text{or} \quad \boxed{G = 6{\cdot}6734 \times 10^{-11} \text{ Nm}^2 \text{ kg}^{-2}}$$

Thus, we can see that the value of *G* in these units is a very, very small number.

Definition of *G* : If we put

$$m_1 = m_2 = 1 \text{ kg}$$

$$r = 1\, m$$

in equation (1), we have

$$F = G\,\frac{1{\cdot}1}{(1)^2} = G$$

Thus, numerically *gravitational constant G may be defined as the force of attraction between two bodies, each of mass 1 kg separated by a distance of 1 m.*

Gravitational force between objects of ordinary size :

The value of the force of attraction between two bodies, each of mass 1 kg separated by a distance of 1 m is

$$F = G\,\frac{(1 \text{ kg}).(1 \text{ kg})}{(1 \text{ m})^2}$$

$$= 6{\cdot}6734 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2} . \frac{1 \text{ kg}^2}{1 \text{ m}^2}$$

$$= \boxed{6{\cdot}6734 \times 10^{-11} \text{ N}}$$

This is a very weak force of attraction.

Again, let us calculate the force of attraction between a student of mass 40 kg and a teacher of mass 60 kg separated by a distance of 1 m in a class-room.

$$F = \frac{(6{\cdot}6734 \times 10^{-11}) \times 40 \times 60}{(1)^2} \text{ N}$$

$$= 1{\cdot}6016 \times 10^{-7} \text{ N}$$

Again, this is a very weak force. That is why we are not aware of any such attraction between objects of ordinary size. You can also see how weak the force of gravitation is when you lift an ordinary sized stone or when a magnet picks up a common pin. Two books lying on a table attract each other due to gravitational force, but the force is so small that we cannot notice it.

Gravitational force between objects of large mass :

Let us now calculate the force of attraction between the earth and a body lying on the surface of the earth. Let the mass of the body be 35 kg. The mass of the earth is about 6×10^{24} kg. The distance separating the body from the centre of the earth is the radius of the earth which is $6{\cdot}37 \times 10^6$ m.

The force of attraction (F) between the earth and the body lying on the surface of the earth is given by

$$F = G.\frac{(6 \times 10^{24}) \times 35}{(6{\cdot}37 \times 10^6)^2} \text{ N}$$

$$= \frac{(6{\cdot}6734 \times 10^{-11})\,(6 \times 10^{24}) \times 35}{(6{\cdot}37 \times 10^6)^2} \text{ N}$$

$$= 345{\cdot}4 \text{ N}$$

This is a *much stronger force* to be felt. We certainly cannot ignore this force.

Let us again calculate the force of attraction (F) between the earth and the moon. Mass of the earth is 6×10^{24} kg; mass of the moon is $7{\cdot}4 \times 10^{22}$ kg and the distance between the earth and the moon is $3{\cdot}84 \times 10^8$ m.

The force of attraction

$$F = \frac{6{\cdot}6734 \times 10^{-11} \times 6 \times 10^{24} \times 7{\cdot}4 \times 10^{22}}{(3{\cdot}84 \times 10^8)^2}$$

$$= 2{\cdot}0 \times 10^{22} \text{ N}$$

It is quite a *large* force.

Thus it is quite clear that we can ignore the force of attraction between objects of ordinary size but we certainly cannot ignore the gravitational force between huge objects *i.e.*, when we deal with the earth, or the moon or the sun or objects with very large masses like 10^{24} kg because the force is enormous. Newton's great contribution was the recognition of the truly *universal* nature of the gravitational force. This gravitational force holds our complex universe together: it keeps the moon in orbit around the earth; it holds the planets in orbit around the sun; it anchors all of us to the earth so that we do not float off into space; and it explains the presence of globular star clusters or galaxies. The constant G has the same value at every place in the universe. Newton's discovery of the law of universal gravitation is sometimes called the greatest single discovery in the history of science.

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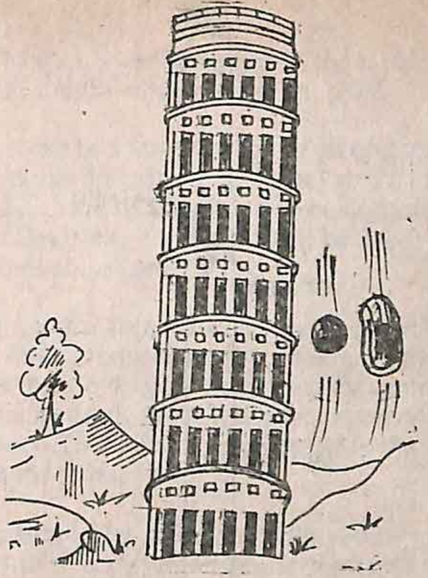
* You will learn about this experiment in higher classes

3.4 FREELY FALLING OBJECTS (FREE FALL)—ACCELERATION DUE TO GRAVITY

In the earlier section in this Chapter, we had observed a falling brick. We noticed that the speed of the brick increased as it fell to the earth. We said that this acceleration was due to the force of attraction between the brick and the earth. Can we measure this acceleration? Will this acceleration be large if the body has a large mass? Will heavier objects accelerate more than lighter ones?

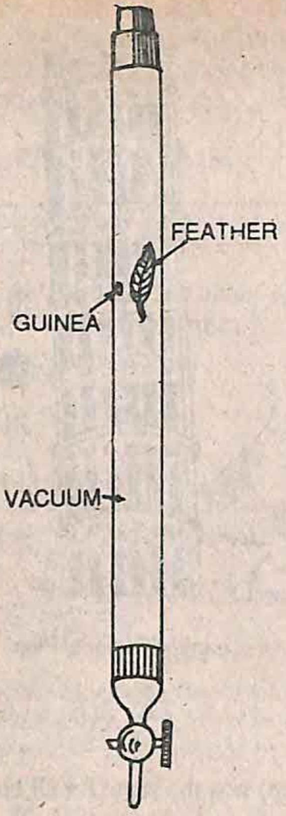
Take a pebble in your one hand and a flat piece of paper from your rough copy in your other hand. Hold the two objects at *equal* heights above the ground and let them go at the same time. You will notice that the pebble falls to the ground much before the flat piece of paper does. You would be tempted to conclude that heavier objects fall faster than lighter ones—the view held by the Greek philosopher aristotle. Again, take the same pebble and the same piece of paper, but this time squeeze this piece of paper into a small paper ball. Repeat the experiment. You will find that the pebble and the paper ball would reach the ground almost at the same time. In other words, the paper, whose mass is the same, whether it is flat or squeezed, falls faster when it is squeezed. This simple activity shows that the speed of a falling body does not depend upon its mass.

In fact Aristotle's view that heavier objects fall faster than lighter ones was the common belief for quite a long time. It was Galileo who decided to test the common feeling experimentally. There is a legend that he dropped two stones of different masses from the top of the Leaning Tower of Pisa (Fig. 3.3). He showed that the rate of fall (or acceleration) was the same for all bodies and did not depend upon their masses. If, however, the experiment is performed very cautiously and time is measured very accurately it will be found that the rate of fall will not be identical for all bodies unless the friction offered by air is eliminated. Galileo attributed the slowing down of lighter bodies (flat piece of paper etc.) to the resistance or the friction offered by air. If there were no air, he said, two objects of different masses would reach the ground together when dropped from the same height. Though Galileo could not show this experimentally, the same was proved by Newton with the help of **feather and guinea experiment.** He took a glass tube of about 2m length and of about 8 cm diameter and sealed at one end. A feather and a guinea were placed in the tube (Fig. 3.4). The open end of the tube was also sealed with a cork having a brass tube provided with a stop-cock which was closed. The tube was then inverted suddenly and it was found that guinea fell down more quickly than the feather. Then the brass tube was connected to an air pump and air from the tube was removed and the experiment was repeated with practically no air in the tube. It was found that both guinea and feather fell down at the same rate when the tube was suddenly inverted.



Learning Tower of Pisa

Fig. 3.3



[Feather and Guinea Experiment]

Fig 3.4

Thus, we conclude that, in the absence of air resistance, all bodies irrespective of their masses fall at the same rate.

We know that a falling object accelerates towards the earth because of the gravitational force of attraction between the object and the earth. We call the force of gravity that acts on an object the *weight* of the object. When this is the only force that acts on an object—that is, when air resistance and the like are negligible—we say that the object is in a state of *free fall*. To say something is freely falling is to say it is falling free of opposing forces of any kind, usually air resistance. The only force that acts on an object in free fall is the force of gravity.

Whereas force of gravity tends to accelerate things when they fall freely, mass (or inertia) tends to resist the acceleration. So twice the force exerted on twice the inertia produces the same acceleration as half the force exerted on half the inertia (Newton's Second Law of Motion). Both accelerate equally. So we see the acceleration of free fall is independent of weight. A boulder 100 times more massive then a pebble falls at the same acceleration as the pebble because although the force on the boulder (it weight) is 100 times greater than the force (or weight) on the pebble, its resistance to a change in motion (mass) is 100 times that of the pebble. The greater force offsets the equally greater mass.

Whenever a body falls freely under the action of gravity an acceleration is produced in it because of the gravitational force of attraction between the body and the earth. This acceleration is know as **acceleration due to gravity.** *It is denoted by the symbol 'g' since it is the same for all freely falling bodies.*

Expression for g :

Let a body of mass m be lying on or near the surface of the earth. Let M be the mass of the earth and R be its radius (Fig. 3.5) which is also the distance of the body from the centre of the earth.

The force of attraction (F) between the earth and the body lying on or near the surface of the earth is given by

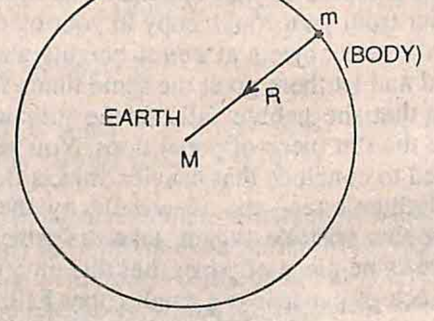


Fig. (3.5)

$$F = \frac{G\,Mm}{R^2}$$ (Newton's Law of Gravitation)

This is the force with which the body will fall freely on the earth if allowed to do so. This force will produce an acceleration due to gravity g in it. According to Newton's second law of motion, the acceleration g of the freely falling body is given by

$$\text{Acceleration} = \frac{\text{Force}}{\text{mass of the body}}$$

or $$g = \frac{F}{m}$$

or $$g = \frac{G\,Mm}{R^2.m}$$

or $$\boxed{g = \frac{G\,M}{R^2}}$$

Notice that this acceleration does not depend on the mass m of the body that falls freely. It only depends on the mass of the earth (M) and the distance of the body (R) from the centre of the earth (which is also the radius of the earth R as the body is near or on the surface of the earth).

Now, if we substitute the values of the mass of the earth and, its radius in the above equation for g, we can get the numerical value of this acceleration.

Mass of the earth (M) $= 6 \times 10^{24}$ kg

Radius of the earth (R) $= 6{\cdot}4 \times 10^6$ m

Gravitational constant $= G$

$= 6{\cdot}67\times10^{-11}\ \text{Nm}^2\,\text{kg}^{-2}$

$$\therefore \text{ Acceleration due to gravity} = g = \frac{GM}{R^2}$$

or $$g = \frac{6{\cdot}67 \times 10^{-11} \times 6 \times 10^{24}}{(6{\cdot}4 \times 10^6)^2}\ \text{ms}^{-2}$$

$$= 9{\cdot}8\ \text{m/s}^2 \approx 10\ \text{m/s}^2$$

Variation of g with latitude and altitude :

The expression $g = \frac{GM}{R^2}$ deduced earlier shows that the value of g must vary with latitude and altitude.

The following reasons for the variation of "g": are worthnoting :

(a) As earth is not a perfect sphere but is slightly bulging out at the equator its radius decreases as we go from the equator to the poles and hence g, which is inversely proportional to the square of the radius, increases as we go from the equator to the poles. At the equator at sea-level its value is about $9{\cdot}78$ m/s^2 and at the poles it is $9{\cdot}83$ m/s^2. Its mean value is taken as $9{\cdot}81$ m/s^2 for all calculations.

(b) Similarly the value of g decreases as we go up to the top of a mountain or higher up in the air. This decrease is given by the formula $\frac{2hg}{R}$ where h is the height above the surface of the earth and R is the radius of the earth at the given point.

(c) It can be shown that the value of g inside the earth varies directly proportional to the distance from the centre of the earth. Hence, g decreases as we go down into the earth till it becomes zero at the centre of the earth.

(d) Another factor which reduces the value of g is the force produced by the rotation of the earth. As this force is directed away from the centre of the earth its tendency is to reduce the acceleration due to gravity. This force is also greater at the equator than at the poles.

Variations of g produce similar variations in the weight of a body as weight is measured by the product mg which varies as g because m the mass of the body is constant.

3.5 MOTION OF A BODY UNDER GRAVITY

In Chapter 2-1.1 (Describing Motion), we obtained the following equations of uniformly accelerated motion

$$v = u + a\,t$$

$$s = ut + \frac{1}{2}\,a\,t^2$$

$$2a\,s = v^2 - u^2$$

We can *also* apply these equations to bodies falling freely under the action of gravity. The motion of a freely falling body is the most common example of a uniformly accelerated motion. Since all bodies, big or small, are observed to fall with the same uniform acceleration g (acceleration due to gravity) if we neglect the resistance due to air, then the acceleration a in the above-mentioned equations of motion is replaced by the acceleration due to gravity g. Writing 'g' in place of 'a' in the equations of uniformly accelerated motion, we have

$v = u + g\,t$ Equations of motion

$s = ut + \frac{1}{2}\,g\,t^2$ of a body under

$2gs = v^2 - u^2$ gravity.

where $g = 9{\cdot}8$ m/s^2.

Bodies projected vertically upwards against gravity

When a body is thrown vertically up with a certain velocity, the gravity acts downwards and its velocity gradually decreases till it comes to rest momentarily and again begins to fall down. In other words, the body ascends with *uniform retardation or negative acceleration i.e.* ,$-g$

$$-g = -9.8 \text{ m/s}^2$$

Negative sign indicates retardation.

Velocity of a body falling from rest from a height

Let a body fall freely from rest from a point at a height h. We have to find its velocity when it has fallen through a height h.

Now,

$$u = 0$$

$$v = ?$$

$$a = g$$

$$s = h$$

$$\text{Since, } v^2 - u^2 = 2as$$

$$\therefore \quad v^2 - 0 = 2gh$$

$$\text{or } v^2 = 2gh$$

$$\text{or} \quad \boxed{v = \sqrt{2gh}}$$

Greatest height attained by a body projected vertically upwards against gravity :

Let a body be projected upwards with an initial velocity u. We have to find the greatest height attained by it.

Now,

$$\text{Initial velocity} = u$$

$$\text{Final velocity } v = 0$$

$$\text{Acceleration} = a = -g$$

$$\text{Height} = S = h = ?$$

$$\because \quad v^2 - u^2 = 2as$$

$$\therefore \quad 0 - u^2 = -2gh$$

$$\text{or} \quad \boxed{h = \frac{u^2}{2g}}$$

Time of ascent

Let a body be projected vertically upwards with an initial velocity u. We have to find the time of ascent *i.e.*,time taken by it to reach the greatest height h.

Now,

$$\text{Initial velocity} = u$$

$$\text{Final velocity } v = 0$$

$$\text{Acceleration} = a = -g$$

$$\text{Time of ascent} = t = ?$$

$$\because \quad v = u + at$$

$$\therefore \quad 0 = u - gt$$

$$\text{or} \quad \boxed{t = \frac{u}{g}}$$

Time of descent

Let a body be projected upwards with an initial velocity u. The greatest height attained by it has been calculated above and is given by

$$h = \frac{u^2}{2g} \qquad \text{... (1)}$$

The time of ascent *i.e.*,the time of attaining this height has also been calculated above and is given by

$$t = \frac{u}{g} \qquad \text{... (2)}$$

After attaining this greatest height, h, the body falls down. We have to find the time of descent *i.e.*, the time taken by it to reach the starting point.

$$\text{Now,} \quad \text{initial velocity } u = 0$$

$$\text{Distance} = s = h = \frac{u^2}{2g}$$

$$\text{Acceleration} = a = g$$

$$\text{Time of descent} = T = ?$$

$$\because \quad S = h = ut + \frac{1}{2} g T^2$$

$$\therefore \quad \frac{u^2}{2g} = 0 + \frac{1}{2} g T^2$$

or $$\boxed{T = \frac{u}{g}} \quad \text{... (3)}$$

The equations (2) and (3) show that the *time of ascent is equal to time of descent.* **Total time of flight** *from the starting point to the highest point and back is equal* to $\frac{u}{g} + \frac{u}{g} = \boxed{\frac{2u}{g}}$.

Velocity of return

Let a body be projected vertically upwards with an initial velocity u. It rises up with a *uniform retardation* due to gravity, attains the greatest height, remains at rest *momentarily* and then begins to fall down under gravity. Clearly, the total time of flight from the starting point and back is $\frac{2u}{g}$ (derived above).

Now, Initial velocity $= u$

Final velocity $= v = ?$

Acceleration $= a = -g$

Total time of flight $= t = \frac{2u}{g}$

$$v = u + at$$

$$v = u - g \cdot \frac{2u}{g}$$

$$= u - 2u$$

$$= -u$$

or $$\boxed{v = -u}$$

Thus, the body returns with a velocity numerically equal to that with which it was projected upwards.

3.6 NEWTON'S THIRD LAW AND GRAVITATION

According to Newton's third law of motion, *"To every action there is always an equal and opposite reaction."* If an object A exerts a force on another object B, then the object B exerts an equal force on the object A in the opposite direction. This is true of the force of gravitation also. For example, we had observed earlier that a brick when dropped accelerates and falls towards the earth. This is due to the gravitational force exerted by the earth on the brick. In fact, the brick also attracts the earth with an equal force. Why then, do we see the brick falling to the earth, but not the earth rising towards the brick ?

It is true that the gravitational pull of the brick on the earth is equal to the pull of the earth on the brick. However, the acceleration produced in the brick and in the earth are not equal since the mass of the earth is much larger as compared to the mass of the brick. Let us find the force exerted by the earth on the brick. Let us take a brick weighing 2 kg. The mass of the earth is 6×10^{24} kg. If the brick and the earth are separated by a distance of $6{\cdot}4 \times 10^6$ m, the force of attraction (F) is

$$F = \frac{G\,mM}{r^2} \quad \text{(Newton's law of gravitation)}$$

where m = mass of the brick

M = mass of the earth

r = distance

G = Gravitational constant

$$= \frac{6{\cdot}6734 \times 10^{-11} \times 2 \times 6 \times 10^{24}}{(6{\cdot}4 \times 10^6)^2} \text{ newton}$$

$$= 19{\cdot}6 \text{ newton}$$

We can now use Newton's second law of motion to find the acceleration a of the brick as it falls to the earth.

$$a = \frac{F}{m} = \frac{19{\cdot}6 \text{ N}}{2 \text{ kg}} = 9{\cdot}8 \text{ ms}^{-2}$$

The stone also pulls the earth with a force of 19·6 N. The acceleration of the earth a_{earth} due to this pull can also be calculated from Newton's second law of motion.

$$a_{earth} = \frac{F}{M} = \frac{19{\cdot}6 \text{ N}}{6 \times 10^{24} \text{ kg}}$$

$$= 3{\cdot}26 \times 10^{-24} \text{ ms}^{-2}$$

Compared to the acceleration of the brick which is $9{\cdot}8$ ms^{-2}, this acceleration of the earth is very very small, that is why we do not see the earth rising towards the falling brick.

However, if there are two objects with comparable masses *i.e.*, m ~ M, their accelerations would be comparable. If the objects are massive, their accelerations would be large and the objects can be seen moving towards each other. In fact, astronomers have observed two such objects in the sky. Two stars Sirius A and Sirius B move around each other because their masses are comparable.

3.7 MEASURING MASS WITH GRAVITY (Mass and weight of an object)

The *mass* of a body is defined as the *quantity of matter in a body.* This matter has the important property of inertia, which means that matter will remain at rest unless moved by an external force. We can thus say that a big stone is more *massive* than a little stone, because it requires a bigger force to make it move. In other words, the larger the inertia a body has, the greater is its mass. The mass of a body defined in terms of its inertia is known as its *inertial mass.*

According to Newton's second law of motion, when an unbalanced force (F) is applied on a body, the body moves with an acceleration (a). Thus

$$F = ma$$

or $m = \frac{F}{a}$ where m is called the *inertial mass* of the body.

If the force is increased, the acceleration also increases and $\frac{F}{a}$ = constant for a given body. If the *same* force is applied on two different bodies, and accelerations produced are equal, then the inertial masses of the two bodies are equal *i.e.*,

$$F = m_1 a = m_2 a$$

$$\therefore \quad m_1 = m_2$$

If the same force is applied on two different bodies of masses m_1 and m_2, then

$$F = m_1 a_1 = m_2 a_2$$

or $\frac{m_1}{m_2} = \frac{a_2}{a_1}$ where a_1 and a_2 are the accelerations produced.

It is clear that if $m_1 > m_2$ then $a_2 > a_1$. In other words, the inertial mass of that body is more in which acceleration produced is less and vice versa.

Mass can also be measured by the attraction to another mass. Two masses can be compared by the amount of attraction to another mass, to the earth for example. Mass detected in that way is called **gravitational mass.**

The **weight** *of a body on earth is defined as the force with which it is attracted by the earth.*

According to Newton's law of gravitation, the gravitational force of attraction of a body towards the centre of the earth is equal to the **weight** (W) of the body

$$F = W = \frac{G\,Mm}{R^2} = mg$$

or $m = \frac{W}{g}$ where m is called the *gravitational mass* of the body; M is the mass of earth having radius R. Thus mass is measured either by its inertia as in Fig. 3.6 (a) or by its gravitational attraction to another mass, such as the earth as in Fig 3.6 (b).

There is no relation between the inertial mass and the gravitational mass of a body. By definition both are two different quantities. But, for all practical purposes, both are taken to be identical.

Both are measured in kilogram (kg).

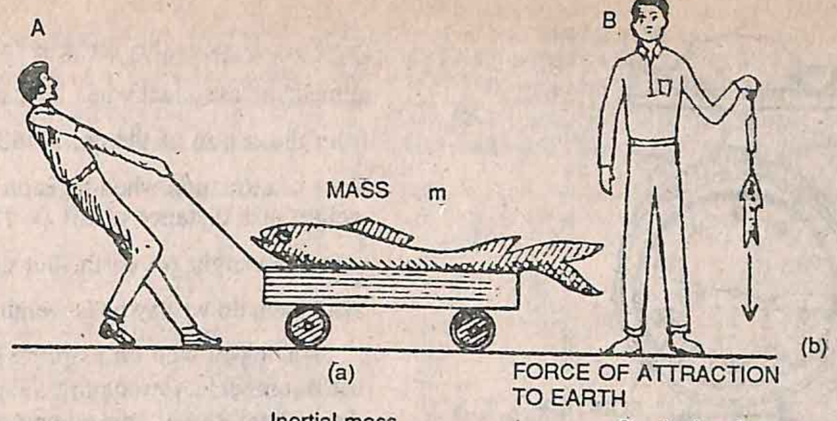
To understand the concept of gravitational mass let us consider two objects of masses m_1 and m_2 lying on the surface of the earth (assumed to be spherical). Let W_1 and W_2 be their weights. Then

$w_1 = \frac{GMm_1}{R^2} = m_1 g$ where g is the acceleration due to gravity ($g = \frac{GM}{R^2}$) and

$$W_2 = \frac{GMm_2}{R^2} = m_2 g$$

$$\therefore \quad \boxed{\frac{m_1}{m_2} = \frac{W_1}{W_2}}$$

If $W_1 = W_2$, then $m_1 = m_2$.


A
B
MASS
m
(a)
FORCE OF ATTRACTION TO EARTH
(b)

Inertial mass

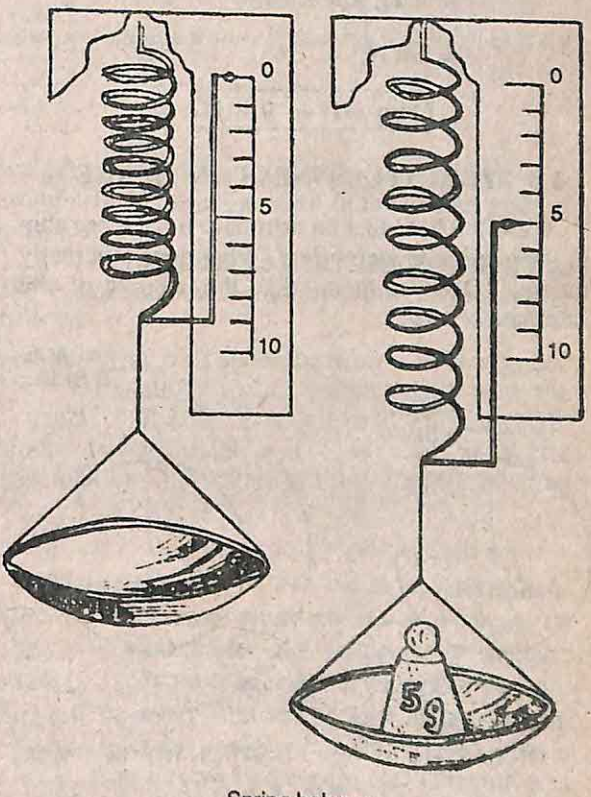
Gravitational mass

Fig. 3.6

This means if two objects when placed at the same distance from the third object (say earth), experience the same gravitational force, then their gravitational masses will be equal. This idea of comparing masses is used by us almost daily with the help of a *beam balance*. For example when we buy five kilogram of mangoes, the fruitseller keeps a standard five kilogram weight (mass of 5 kg) on one pan of the balance and mangoes on the other. He then adjusts the quantity of mangoes till the beam of the balance is *horizontal*. In balanced position, the force of earth's gravity on one pan becomes equal to that on the other. Therefore, the mass of the mangoes on the pan will be equal to that of the standard "5 kilogram weight" placed in the other pan.

The gravitation mass of the body will be the same even on the surface of the moon. If the value of 'g' is less on the moon, the weight of the body will also be less but the gravitational mass is the same. In otherwords, the mass of an object does not change from place to place whereas the weight changes as the force of gravity (or acceleration due to gravity g) undergoes a change from one place to another.

The weight of a body, which is a force, can be measured by means of a *spring balance*. Coil springs are used in the spring balance for measuring force. It is found that *the change in length of a spring is directly proportional to the force acting on it* (Fig. 3.7). The spring balance and the compression balance (Fig. 3.8) are all direct measuring instruments previously graduated by using standard masses. You need only to put the body whose weight you want to find on the scale pan or hang it from the hook and take the reading as shown by the pointer moving along a scale. Some spring balances are marked to measure force in *newton* (N) whereas most spring balances are marked in kilogram (or gram). You must, however, remember that what operates a spring balance is a force and not just mass.

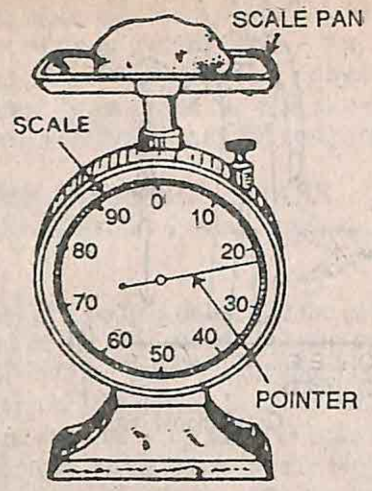


Spring balance

Fig. 3.7

In the SI system, the unit of weight is *newton* (N) and that of mass is *kilogram* (kg). Weight is a *Vector* quantity and mass is a *scalar* quantity.

The weight of a mass of 1 kg on earth is called a *kilogram weight* (kg wt).



Compression balance

Fig. 3.8

$$1 \text{ kg wt} = mg$$

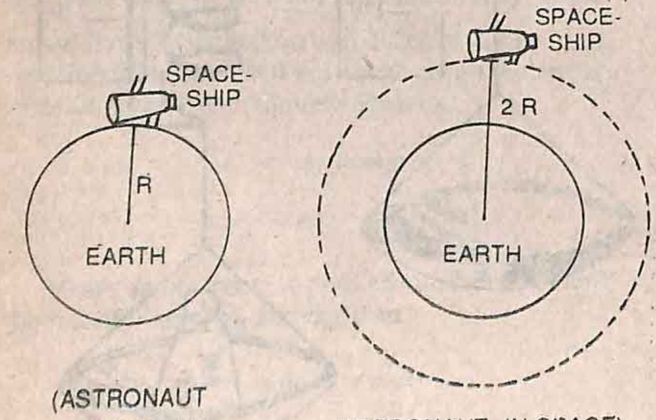
$$= 1 \text{ kg} \times 9{\cdot}8 \text{ ms}^{-2}$$

$$= 9{\cdot}8 \text{ N}$$

$$\therefore \quad \boxed{1 \text{kg wt} = 9{\cdot}8 \text{ N}}$$

3.8 WEIGHTLESSNESS IN SPACE*

We often hear that an astronaut in a space-ship in deep space is *weightless*. What does this really mean ? Does it mean that the weight of the astronaut is zero?



(ASTRONAUT ON EARTH)

(ASTRONAUT IN SPACE)

Fig. 3.9

Suppose the-space ship is orbiting at a distance of 2R from the centre of the earth where R is the radius of the earth which is 6400 km (Fig 3·9). We know that the gravitational force of attraction *decreases* as the square of the distance (*i.e.*, $F \propto \frac{1}{R^2}$). Hence, the force with which the earth attracts the astronaut when he is at a distance of 2R from the centre of the earth will be $\frac{1}{4}$ times the force of attraction when he is on earth. That is, his weight at a distance of 2R (= 12800 km) will be $\frac{1}{4}$ th his weight on earth, but certainly not zero. Why then, do we say he is weightless?

When you step on a spring balance such as a bathroom scale, you compress a spring inside. When the pointer stops, you compress a spring inside. When the pointer stops, the strong electrostatic forces between the molecules inside the spring material balance gravitational attraction between you and the earth — nothing moves as you and the scale are in static equilibrium. The pointer is calibrated to show your weight. If you stood on a bathroom scale in a moving elevator, you'd find variations in your weight. If the elevator accelerated upward, the springs inside the bathroom scale would be more compressed and your weight reading would increase. If the elevator accelerated downward, the springs inside the scale would be less compressed and your weight reading would decrease. If the elevator cable broke and the elevator fell *freely*, the reading on the scale would go to zero. According to the reading, you would be weightless. Would you really be weightless ? We can answer this question only if we agree on what we mean by *weight*.

We define the weight of something as the force it exerts against the supporting floor or the weighing scales. According to this definition, you are as heavy as you feel; so in an elevator that accelerates downward, the supporting force of the floor is less and you weigh less. If the elevator is in free fall, your apparent weight is zero (Fig. 3.10). Even in this weightless condition, however, there is still a gravitational force acting on you, causing your downward acceleration. But gravity now is not felt as weight because there is no support force.

Consider an astronaut in orbit. The astronaut is in a state of apparent weightlessness. He feels weightless because he is not supported by anything (Fig. 3.11). There would be no compression in the springs of a bathroom scale placed beneath his feet because the bathroom scale is falling as fast as he is. Any objects that are released fall together with him and remain in his vicinity, unlike what happens on the ground. All the local effects of gravity are eliminated. The body organs respond as though gravity forces were absent, and this gives the sensation of weightlessness. The astronaut experiences the same sensation in orbit that he would feel in a falling elevator—a state of free fall.

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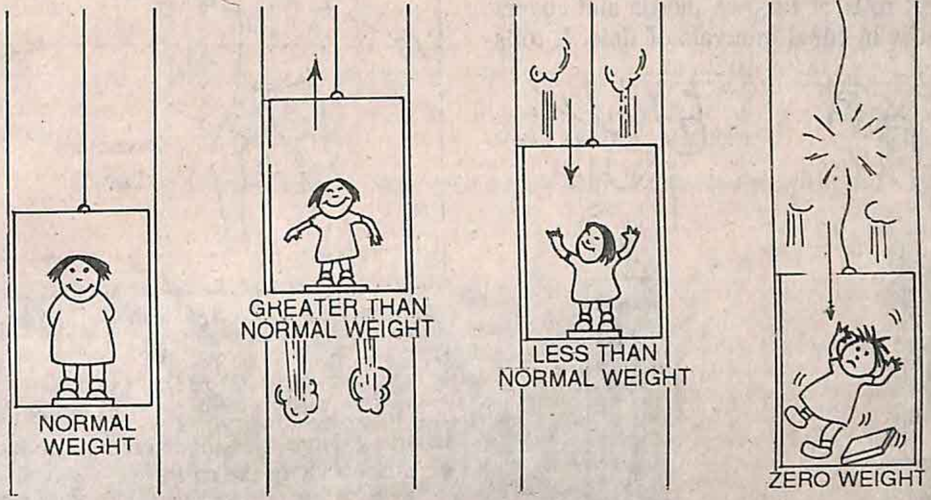
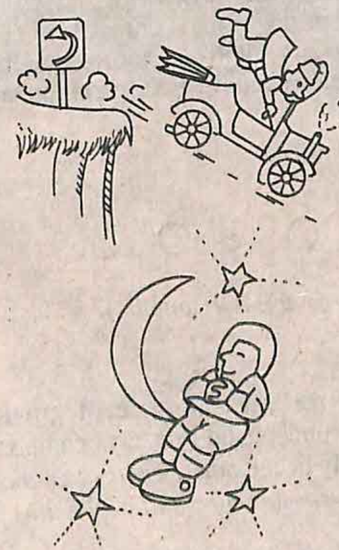
* For further knowledge only. Not to be tested



(The sensation of weight equals the force with which you press against the supporting floor. If the floor accelerates up or down, your weight varies.)

Fig. 3.10

Note that the astronaut is still under the influence of gravitational force, constantly changing his direction (his velocity), thus accelerating. That's why we say he is in a state of *apparent* weightlessness. To be truly weightless, he would have to be far out in space, well away from the earth, sun and other attracting bodies, where gravitational forces are negligible. In this truly weightless condition, any motion would be in a straight-line path rather than in the curved path of closed orbit.



(Both are "weightless.")

Fig. 3.11 (a)

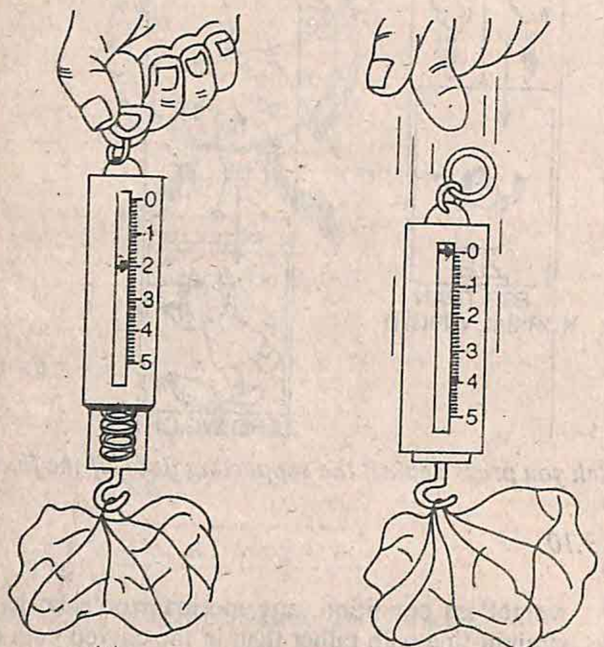
You can demonstrate weightlessness under free fall by holding a heavy object at the end of a spring balance.

The spring will show the weight of the object. Now release the spring balance and read the "weight" as it falls. You will find that the weight shown by the balance will be zero. Will you conclude that the object is truly weightless? [See Fig. 3.11 (a) and (b)].

3.9 PROJECTILES AND PLANETS

A projectile may be defined as a body which after having been given an initial velocity is allowed to move under the influence of gravity alone i.e., it is no longer being propelled by any fuel *e.g.*, a javelin thrown by an athlete, a bomb released from an aeroplane; a bullet shot from a rifle; a stone thrown into the air etc. The path of a projectile is called its *trajectory* (curved path) [Fig (3.12 (a)]. At first thought the trajectory seems rather complicated. However, it will seem surprisingly simple when we look at the horizontal and vertical components of motion separately.

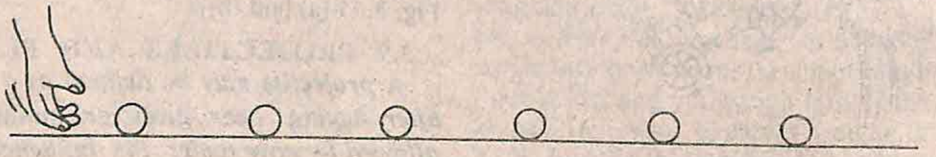
The horizontal component of motion for a projectile is no more complex than the horizontal motion of a bowling ball rolling freely along a level surface. If the retarding effect of friction can be ignored, the bowling ball moves at constant velocity. Since there is no force acting horizontally on the ball, it rolls of its own inertia and covers equal distances in equal intervals of time. It rolls without accelerating. The horizontal part of a projectile's motion is just like the bowling ball's motion along the level surface [Fig. 3.12 (b)]



(a)
(The spring balance shows the weight of the stone)

(b)
(Freely falling spring balance with the stone shows a zero reading)

Fig. 3.11 (b)

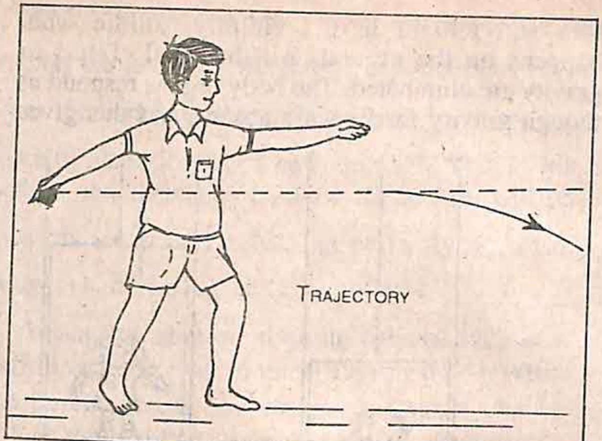


(Velocity is constant because no gravitational force acts horizontally).

Fig. 3.12 (b)

We have studied the motion of an object like the stone accelerating towards the earth (falling freely under gravity). When released with zero velocity *i.e.*, from rest, it will travel a vertical distance S given by

$$S = \frac{1}{2} g t^2$$



Trajectory of a stone thrown horizontally

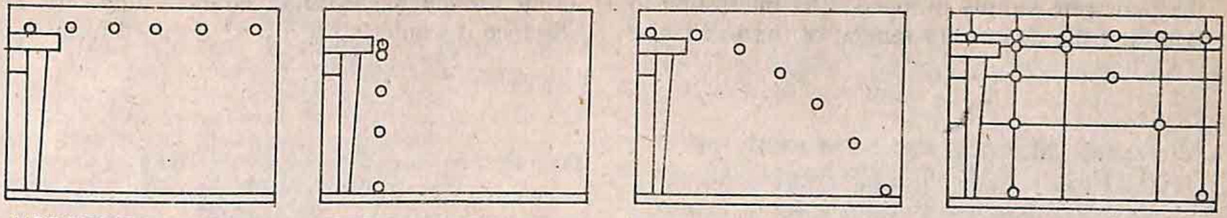
Fig. 3.12 (a)

in time t. Here, g is the acceleration due to gravity on the surface of the earth.

The vertical component of motion for a projectile following its trajectory is just like the motion described above for a freely falling object. Like a ball dropped in mid-air, the projectile moves in the direction of earth gravity and accelerates downward (Fig. 3·13). The increase in speed in the vertical direction causes successively greater distances to be covered in each successive equal-time interval.

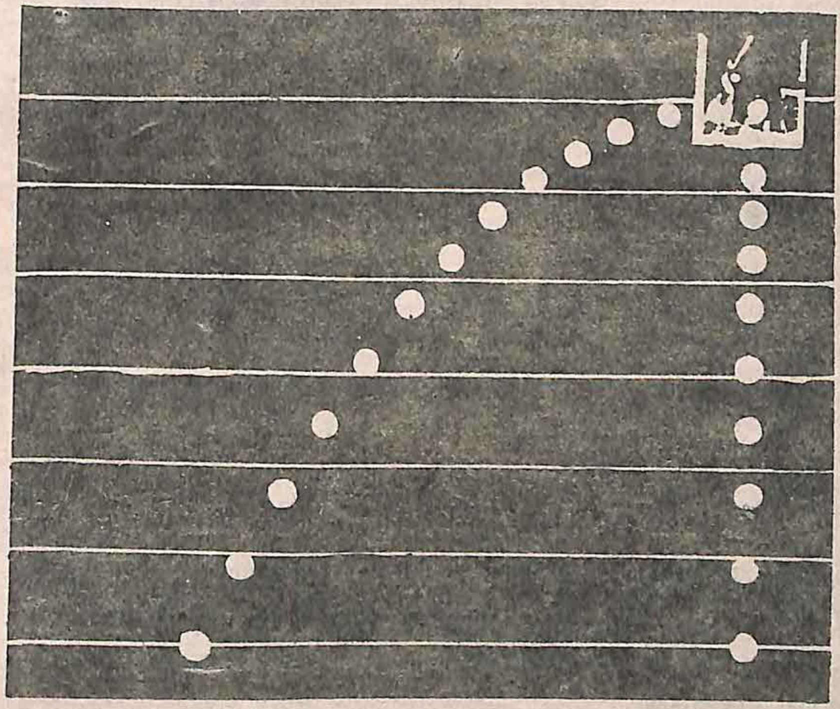
Interestingly enough, the horizontal component of motion for a projectile is completely independent of the vertical component of motion. Unless air drag or some other horizontal force acts, the constant horizontal velocity component is not affected by the vertical force of gravity. It is important to understand that each component acts independently of the other. *Their combined effects produce the curved paths that projectiles follow.*

These ideas are neatly illustrated in the simulated multiple-flash exposure in Fig. 3·14, which shows equally timed successive positions for a ball rolled off a horizontal table. Investigate the figure carefully, for there's a lot of good physics there.


HORIZONTAL MOTION WITH NO GRAVITY
VERTICAL MOTION ONLY WITH GRAVITY
COMBINED HORIZONTAL AND VERTICAL MOTION
SUPERPOSITION OF CASES

(Simulated photographs of a moving ball illuminatea with a strobe light)

Fig. 3.14



(A strobe-light photograph of two balls released simultaneously from a mechanism that allows one ball to drop freely while the other is projected horizontally)

Fig. 3.15

Drop a ball and it accelerates downward and covers a greater vertical distance each second

Fig. 3.13

The curved path of the ball is best analyzed by considering the horizontal and vertical components of motion separately. There are two important things to notice. The first is that the ball's horizontal component of motion doesn't change as the falling ball moves sideways. The ball travels the same horizontal distance in the equal times between each flash. That's because there is no component of gravitational force acting horizontally. Gravity acts only downward, so the only acceleration of the ball is downward. The second thing to note from the figure is that the vertical positions become farther apart with time. The distances travelled vertically are the same as if the ball were simply dropped. It is interesting to note that the downward motion of the ball is the same as that of free fall. Fig. 3·15 is an actual strobe-light photograph of two balls released simultaneously.

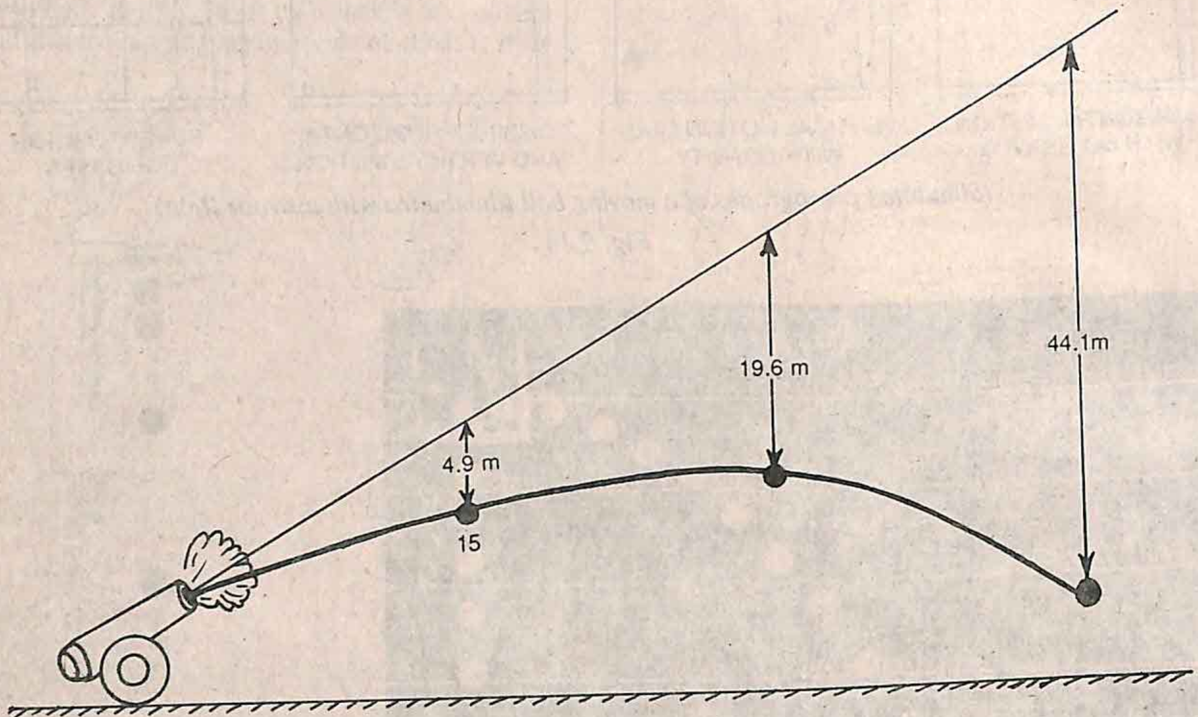


Fig. 3.16

The path traced by a projectile that accelerates only in the vertical direction while moving at a constant horizontal velocity is a ***parabola***. When air resistance can be neglected—usually for slow-moving projectiles or ones very heavy compared to the forces of air resistance—the curved paths are parabolic.

Consider a cannonball shot at an upward angle (Fig. 3·16). Pretend for a moment that there is no gravity; according to the law of inertia, the cannonball would follow the straight-line path shown by the line. But there is gravity, so this doesn't happen. What really happens is that the cannonball continually falls beneath the imaginary line until it finally strikes the ground. Get this : The vertical distance it falls beneath any point on the dashed line is the same vertical distance it would fall if it were dropped from rest and had been falling for the same amount of time. This distance is given by $S = \frac{1}{2} gt^2$, where t is the elapsed time.

We can put it another way : Shoot a projectile skyward at some angle and pretend there is no gravity. After so many seconds t, it should be at a certain point along a straight line path. But because of gravity, it is not. Where is it? The answer is that it is directly below this point. How far below? The answer in metres is $4{\cdot}9\ t^2$. How about that!

Note another thing from Fig. 3·16. The cannonball moves equal horizontal distances in equal time intervals. That is because no acceleration takes place horizontally. The only acceleration is vertically, in the direction of earth's gravity. The vertical distance it falls below the imaginary straight-line path during equal time intervals continually increases with time.

In order to learn more about the motion of projectiles, the students can perform the following simple activity :

Take two coins and place them next to each other on the edge of a table. Now flick away one of the coins parallel to the ground and release the second so that it just topples over (Fig. 3.17). Take care to ensure taht both coins leave the table at the same time. Do the coins hit the ground simultaneously ? You can decide this by listening to the clink of the coins as they reach the ground. If you hear only one clink you can conclude that they hit the ground simultaneously. If you hear two distinct clinks, you can be sure that the coins reach the ground at different times.

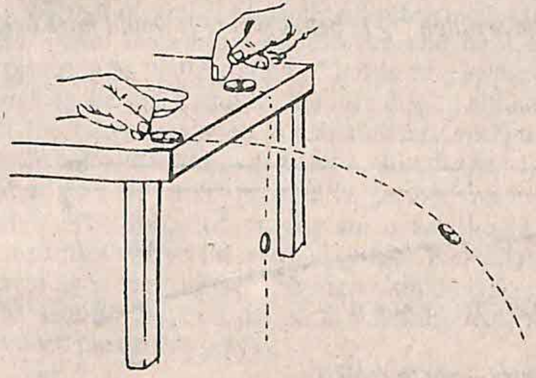


Fig (3·17)

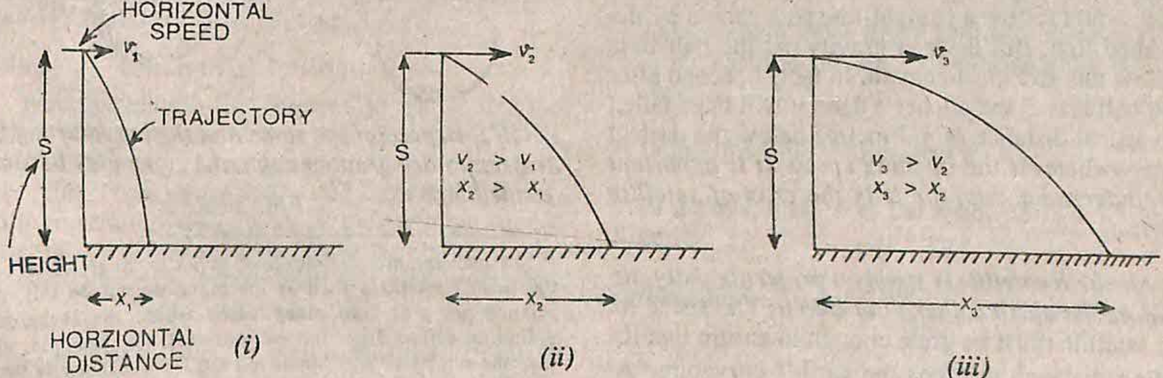
If you perform this activity carefully, you will notice that both coins take the same amount of time to travel the vertical distance from the table to the ground. You can try this activity by flicking one of the coins with different speeds or from tables of different heights. As long as your flick is parallel to the surface and both coins leave the edge of the table simultaneously, the coins will hit the ground at the same time.

This shows that in any given time interval, the vertical distance travelled by an object thrown parallel to the surface of the earth is the same as that travelled by an object released from the same height. Fig. 3·15 shows this fact pictorially if the two balls are replaced by two coins. Notice how both coins are at the same height at any given time.

Thus, we find that the horizontal and vertical motions of a projectile are *independent* of each other. This follows from the fact that the time taken to reach the ground by a body projected horizontally is the same as if it were just dropped freely from that height. Hence the relation between the vertical distance (S) travelled in time t is given by $S = \frac{1}{2} gt^2$.

However, the ***horizontal distance*** travelled by a projectile ***will not be the same***. It will ***depend upon the initial speed*** with which a projectile is thrown. The larger the speed with which it is thrown, the larger is the horizontal distance travelled. Fig. 3.18 shows the trajectories of objects thrown parallel to the ground with different speeds. Notice how the horizontal distance covered increases as the throwing speed increases.

Such falling objects are called projectiles (that is, those which are projected or thrown).



(i) *(ii)* *(iii)*

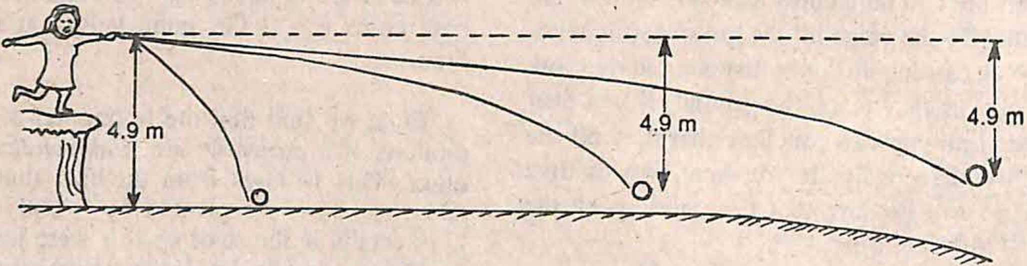
[The horizontal distance travelled by a projectile increases with increase in initial horizontal speed.]

Fig. 3.18

Fast-Moving Projectiles—Satellites

Baseball games normally take place on level ground. For the short-range projectile motion on the playing field, the earth can be considered to be flat because the flight of the baseball is not affected by the earth's curvature. For very long-range projectiles, however, the curvature of the earth's surface must be taken into account. We will now see that if an object is projected fast enough, it will *fall* all the way *around* the earth and be an *earth satellite*. Consider the ball thrown from the cliff in Fig. 3·19. If gravity did not act on the ball, the ball would follow a straight-line path shown by the dashed line. But there is gravity so the ball falls below this straight-line path. In fact, 1 second after the ball leaves the pitcher's hand it will have fallen a vertical distance of 4·9 metres below the dashed line—whatever the pitching speed. *It is important to understand this, for it is the crux of satellite motion.*

***An earth satellite** is simply a projectile that falls **around** the earth rather than **into** it.* The speed of the satellite must be great enough to ensure that its falling distance matches the earth's curvature.[*] A geometrical fact about the curvature of our earth is that its surface drops a vertical distance of 4·9 metres for every 8000 metres tangent to the surface (Fig. 3·20).[+] This means that if you were floating in a calm ocean, you would be able to see only the top of a 4·9 metre mast on a ship 8 kilometres away. So if a baseball could be thrown fast enough to travel a horizontal distance of 8 kilometres during the time (1 second) it takes to fall 4·9 metres, then it would follow the curvature of the earth. A little thought will show that this speed is 8 kilometres per second. If this doesn't seem fast, convert it to kilometres per hour and you get an impressive 29,000 kilometres per hour.



(Throw a stone at any speed and 1 second later it will have fallen 4·9 m below where it would have been without gravity)

Fig. 3·19

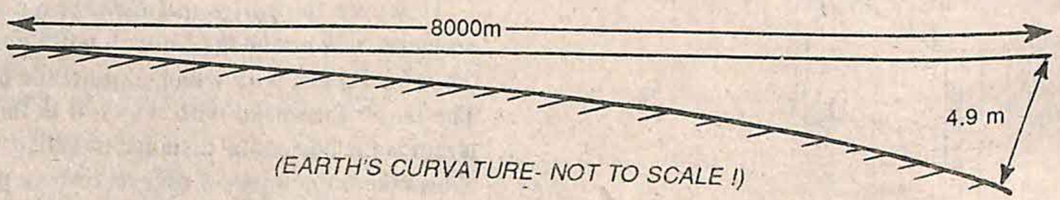
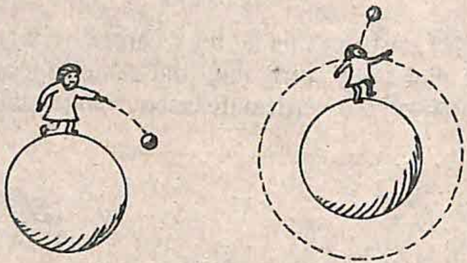


Fig. 3.20 (Earth's curvature—not to scale!)



(If the speed of the stone and the curvature of its trajectory are great enough, the stone may become a satellite.)

Fig. 3·21

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[*] The conventional definition of *to fall* is "to get closer to the earth", satellites such as the moon do not do this. In science we will find many cases where the technical definition differs from the conventional. For example, we say "the sun rises" and "the moon sets," but technically they do not.

[+] A tangent to a circle or to the earth's surface is a straight line that touches the circle or surface at one place, so it is parallel to the circle at the point of contact.

(The space shuttle is a projectile in a constant state of free fall. Because of its tangential velocity, it falls around the earth rather than vertically into it.)

Fig. 3·22

At this speed, atmospheric friction would burn the baseball or even a piece of iron to a crisp. This is the fate of grains of sand and other meteorites that graze the earth's atmosphere and burn up, appearing as "falling stars". That is why satellites such as the space shuttles are launched to altitudes of 150 kilometres or so. A common misconception is that satellites orbiting at high altitudes are free from gravity. Nothing could be further from the truth. The force of gravity on a satellite 150 kilometres above the earth's surface is nearly as great as at the surface. The high altitude is to put the satellite beyond the earth's atmosphere, not beyond the earth's gravity.

The moon is the ***natural satellite*** of the earth. The first artificial (*i.e.*, man-made) satellite was launched by U.S.S.R. in 1956. Since then many artificial satellites have been launched and put into orbit several hundred kilometres above the surface of the earth. India launched its first satellite —ARYABHATTA on 19th April, 1975.

Moon is constantly falling **

Newton was the first scientist to realize that the moon is a satellite of the earth (a projectile). It has just the right speed to keep circling the earth. It completes one such circle in 27 days and 8 hours. It is constantly falling towards the earth but cannot hit the earth because the earth's surface curves down under it by the same amount. Let us calculate the vertical distance the moon falls in 2 days.

The force (F) with which the earth pulls the moon is given by Newton's law of gravitation

$$F = \frac{GM_eM_m}{R^2} \qquad ...(1)$$

Where M_e = mass of the earth

M_m = mass of the moon

R = distance between the earth and the moon.

and G = universal gravitational constant.

From Newton's second law of motion, the acceleration 'a' of the moon is given by

$$= \frac{F}{M_m} = \frac{GM_eM_m}{R^2.M_m} = \frac{GM_e}{R^2} \qquad ...(2)$$

Since all falling objects travel a vertical distance given by the relation :

$$\text{Vertical distance} = \frac{1}{2}at^2$$

$$= \frac{1}{2}\frac{GM_e}{R^2}.t^2$$

$$= \frac{1}{2}.\frac{GM_e}{R_e^2}.\frac{R^2_e}{R^2}.t^2$$

$$= \frac{1}{2}g.\frac{R^2_e}{R^2}.t^2$$

as $g = \frac{GM_e}{R_e^2}$ where R_e is the radius of the earth.

Astronomers have found that the distance (R) from the earth to the moon is 60 times the radius of the earth (R_e).

Using this information, $R = 60\ R_e$

In 2 days, therefore, the moon falls a vertical distance :

$$\text{Vertical distance} = \frac{1}{2}g\frac{R_e^2}{(60R_e)^2}(2 \times 24 \times 60 \times 60)^2$$

$$= \frac{1}{2} \times 9{\cdot}8 \times \frac{1}{3600} \times (48 \times 3600)^2\ \text{m}$$

** For knowledge sake only—not to be tested.

$$= 40642000 \text{ m}$$

$$= 40642 \text{ km}$$

Scale drawing of the motion of the moon in its orbit

Let us test whether this distance predicted by the law of gravitation is correct. Let us calculate the distance through which the moon falls in two days by making a scale drawing of the orbit of the moon. Fig. 3·23 shows the circular orbit of the moon. The scale used is 50,000 km = 1 cm. The orbit of the moon which is a circle of radius R = 384400 km is shown by a circle of radius 7·7 cm. In 27 days the moon covers an angle of 360°. In 2 days, therefore, it will traverse through an angle of 26·6 degrees. The point P, therefore, represents the position of the moon after 2 days. The distance that the moon falls is, therefore, represented by the length AC which, in the drawing, is 8 mm. Multiplying by the scale factor 50,000, we get the actual distance through which the moon falls in two days equal to 40,000 km. This answer is very close to the value predicted from the law of gravitation.

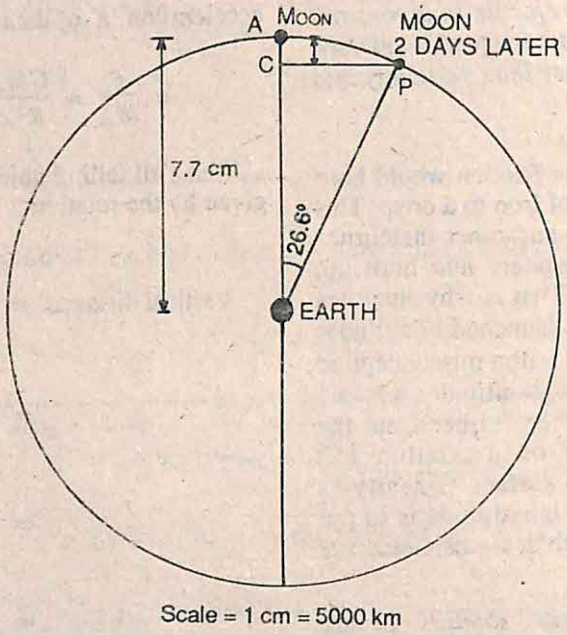


Fig. 3·23 Scale drawing of the motion of the moon in its orbit Scale, 1 cm = 50000 km

It was Newton who first calculated this result to test his law of gravitation. This calculated distance agreed beautifully with the observed orbit of the moon. Then Newton knew that the law of gravitation which he had proposed must be right.

We can perform the same calculation for the planets which orbit round the sun. It is the gravitational attraction of the sun that keeps the planets in their orbits, just as the moon goes round the earth due to the attraction of the earth (Fig. 3·24).

SOLVED EXAMPLES

Example 1: Calculate the gravitational force exerted by the sun on the earth using the following data :

Mass of the sun = $m_s = 1{\cdot}99 \times 10^{30}$ kg

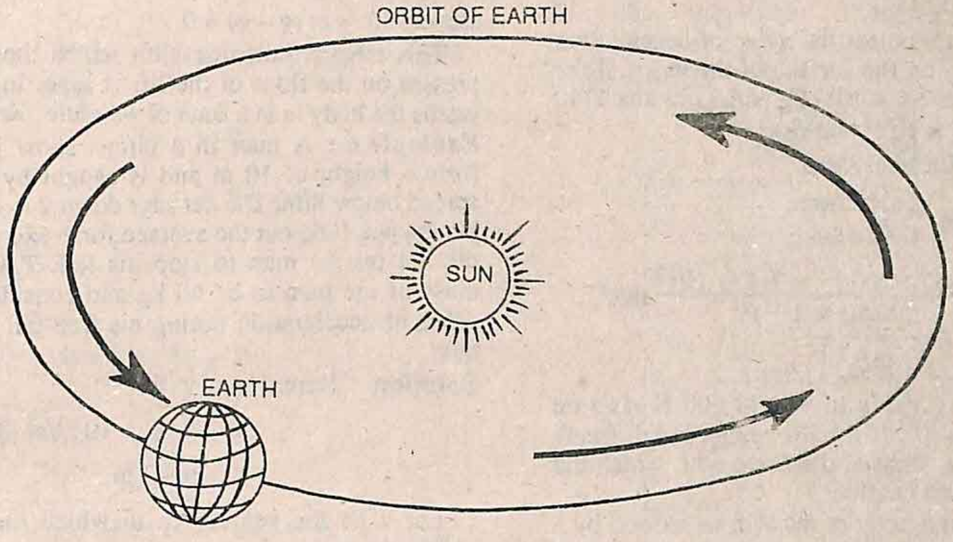
Mass of the earth = $m_e = 5{\cdot}98 \times 10^{24}$ kg

Distance between the centres of the sun and the earth = $r = 1{\cdot}49 \times 10^{11}$ m

$G = 6{\cdot}67 \times 10^{-11}$ N m^2/kg^2

Solution : From Newton's law of universal gravitation we have for the magnitude of the gravitational force F

$$F = \frac{Gm_s m_e}{r^2}$$



(Earth in its orbit around the sun)

Fig. 3·24

where m_s is the mass of the sun, m_e is the mass of the earth and r is the distance between the centres of the sun and the earth.

Hence,

$$F = \frac{(6{\cdot}67 \times 10^{-11})\ (1{\cdot}99 \times 10^{30})\ (5{\cdot}98 \times 10^{24})}{(1{\cdot}49 \times 10^{11})^2}$$

$$= 3{\cdot}58 \times 10^{22} \text{ kg. m/s}^2$$

$$= \boxed{3{\cdot}58 \times 10^{22} \text{ N}}$$

It is this enormous force of $3{\cdot}58 \times 10^{22}$ N which keeps the earth moving in its elliptical orbit about the sun. If it ceased to exist, the earth would go flying off in a straight line tangent to its original orbit.

Example 2 : If 9×10^7 N existed as the force of gravitation between the earth and a body of mass m on its surface, what would be the value of m? Take mass of the earth = 6×10^{24} kg and

$$G = 6{\cdot}67 \times 10^{-11} \text{ N m}^2/\text{kg}^2$$

Radius of the earth = $6{\cdot}4 \times 10^3$ km

Solution: According to Newton's law of gravitation,

$$F = \frac{GMm}{r^2}$$

where F = force of gravitation

M = mass of the earth

r = radius of the earth

$$\therefore\ 9 \times 10^7 = \frac{6{\cdot}67 \times 10^{-11} \times 6 \times 10^{24} \times m}{(6{\cdot}4 \times 10^6)^2}$$

or mass of the body = m

$$= \frac{9 \times 10^7 \times (6{\cdot}4 \times 10^6)^2}{6{\cdot}67 \times 10^{-11} \times 6 \times 10^{24}} \text{ kg}$$

$$= \boxed{9{\cdot}2 \times 10^6 \text{ kg}}$$

Example 3 : Calculate the force of gravity on a body of mass 100 kg placed on the surface of the earth ($g \approx 10 \text{ ms}^{-2}$).

Solution: Force of gravity is the force with which the earth attracts a body towards its centre lying on its surface. The magnitude of this force = mg where m is the mass of the body and g is its acceleration due to gravity.

$$= 100 \times 10 \text{ as } g \approx 10 \text{ m/s}^2$$

$$= \boxed{1000 \text{ N}}$$

Example 4: Calculate the value of acceleration due to gravity on the surface of the moon. Take mass of moon $7{\cdot}4 \times 10^{22}$ kg and its radius 1740 km. $G = 6{\cdot}67 \times 10^{-11}$ Nm²/kg².

Solution : We know that

$$g_{moon} = \frac{GM_{moon}}{R^2_{moon}}$$

$$= \frac{6{\cdot}67 \times 10^{-11} \times 7{\cdot}4 \times 10^{22}}{(1740 \times 10^3)^2} \text{ m/s}^2$$

$$= \boxed{1{\cdot}63 \text{ m/s}^2}$$

Example 5 : A body of weight 600 N rests on the floor of a lift. If the lift begins to fall freely under gravity, what is the force with which the body presses on the floor ?

Solution: Let a body of mass m be carried by a lift moving downwards with uniform acceleration *a* (Fig. 3·25).

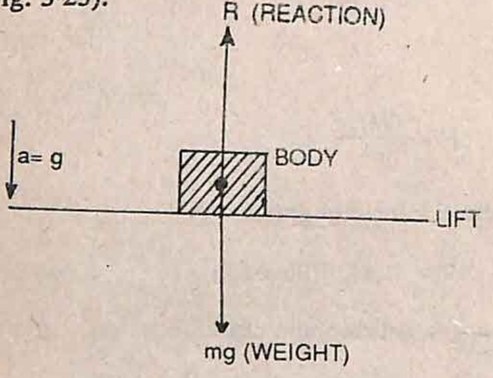


Fig. 3.25

Let us find the pressure on the floor of the lift. The forces acting on the body are :

(1) The reaction R of the plane of the lift upwards which is equal and opposite to the pressure which the mass exerts on the plane.

(2) The weight mg acting vertically downwards. The total force acting downwards on the mass is (mg – R). This force is responsible for moving downwards the mass m with uniform acceleration a.

By Newton's second law of motion, we have

Force = Mass × Acceleration

$mg - R = m \times a$

or $R = m\,(g - a)$

If the lift begins to fall freely under gravity then

$$a = g$$

Hence, $R = m\,(g - g) = 0$

This means the force with which the body presses on the floor of the lift is *zero*. In other words the body is in a state of *weightlessness.*

Example 6 : A man in a circus show jumps from a height of 10 m and is caught by a net spread below him. The net sags down 2 m due to his impact. Find out the average force exerted by the net on the man to stop his fall. Take the mass of the man to be 60 kg and consider the value of acceleration during his free fall as 10 m/s².

Solution : Here, $u = 0$

$a = g = 10 \text{ m/s}^2$

$s = 10 \text{ m}$

Let v be the velocity with which the man strikes the net.

$\therefore \quad v^2 - u^2 = 2as$

or $\quad v^2 - 0 = 2 \times 10 \times 10$

or $\quad v^2 = 200$

or $\quad v = 10\sqrt{2}$ m/s

Let F be the average force exerted by the net on the man to stop his fall. For this journey,

Initial velocity = $10\sqrt{2}$ m/s

Final velocity = 0

Retardation = a = ?

Distance covered = 2 *m*

$\therefore \quad v^2 - u^2 = 2as$

$\therefore \quad (0)^2 - (10\sqrt{2})^2 = 2a \times 2$

or retardation $= a = -50 \text{ m/s}^2$

Since $m = 60$ kg

$\therefore$ Average Force $= ma$

$= 60 \times 50$

$= \boxed{3000 \text{ N}}$

Example 7 : A stone is dropped from the edge of the roof

(a) how long does it take to fall 4·9 m?

(b) how fast does it move at the end of that fall?

(c) how fast does it move at the end of 7·9 metres?

(d) what is its acceleration after 1 second and after 2 seconds?

Solution : When a stone is dropped, its initial velocity is zero.

$$u = 0$$

$$g = 9{\cdot}8 \text{ ms}^{-2}$$

(a) $$s = ut + \frac{1}{2}gt^2$$

$$4{\cdot}9 = 0 + \frac{1}{2} \times 9{\cdot}8 \times t^2$$

$$t^2 = 1$$

$$\therefore \quad \boxed{t = 1 \text{ second}}$$

Thus, the stone takes 1s to fall 4·9 m.

(b) $$v = u + gt$$

$$= 0 + 9{\cdot}8 \times 1$$

$$= \boxed{9{\cdot}8 \text{ m/s}}$$

The stone moves with a velocity of 9·8 m/s at the end of 4·9 m fall.

(c) $$v^2 - u^2 = 2gs$$

$$v^2 - (0)^2 = 2\,(9{\cdot}8)\,7{\cdot}9$$

or $$v^2 = 154{\cdot}84$$

$$\therefore \quad v = \sqrt{154{\cdot}84} = \boxed{12{\cdot}44 \text{ m/s}}$$

The stone moves with a velocity of 12·44 m/s at the end of 7·9 m.

(d) Since the stone is falling freely under the action of gravity, its motion is called ***uniformly accelerated motion.*** Thus its acceleration known as acceleration due to gravity (g) is constant at every moment during its free fall. Hence, the acceleration of the stone is $a = g = 9{\cdot}8 \text{ m/s}^2$ after 1 second as well as after 2 seconds.

Example 8 : A stone drops from the edge of the roof. It passes a window 2 m high in 0·1 second. How far is the roof above the top of the window? ($g = 9{\cdot}8 \text{ m/s}^2$)

Solution : Refer to Fig 3·26 where R is the edge of the roof and $PQ = 2$ m is the height of a window. The stone is dropped from the edge R of the roof. Let its velocity when it reaches P (the top of the window) be v_1. The stone covers the distance $PQ = 2$ m in 0·1 second (given). Thus for distance PQ,

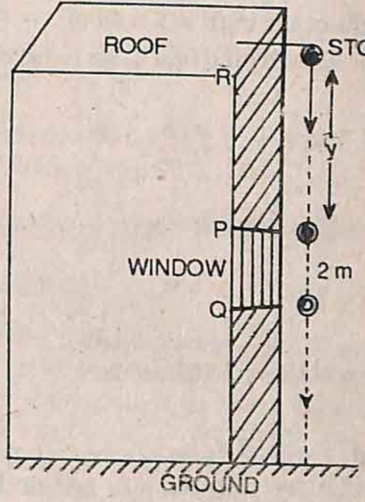


Fig. 3.26

Initial velocity $= v$

Height $= S = PQ = 2\text{m}$

Time taken $= t = 0{\cdot}1$ second

Since, $$s = ut + \frac{1}{2}gt^2$$

$$\therefore \; 2 = v \times 0{\cdot}1 + \frac{1}{2} \times 9{\cdot}8 \times (0{\cdot}1)^2$$

or $v = 19{\cdot}51$ m/s

Let y be the distance of the roof from the top of the window.

For this distance,

Initial velocity $= u = 0$

Final velocity $= v = 19{\cdot}51$ m/s

Distance travelled $= y = ?$

Since, $2gy = v^2 - u^2$

$$\therefore \; 2 \times 9{\cdot}8 \times y = (19{\cdot}51)^2 - (0)^2$$

$$\therefore \; y = \boxed{19{\cdot}42 \text{ m}}$$

Example 9: A boy on a cliff 49 m high drops a stone. One second later he throws a second stone after the first. They both hit the ground at the same time. With what speed did he throw the second stone? ($g = 9{\cdot}8\ m/s^2$)

Solution : First stone :

Initial velocity of the first stone $= u_1 = 0$

Acceleration due to gravity $= g = 9{\cdot}8\ m/s^2$

Height of the cliff $= S = 49$ m

Time taken by the first stone to hit the ground $= t_1 = ?$

Since $S = u_1 t_1 + \frac{1}{2} g t_1^2$

$$\therefore \quad 49 = 0 + \frac{1}{2} \times 9{\cdot}8 \times t_1^2$$

or $t_1^2 = 10$

$$\therefore \quad t_1 = \sqrt{10} = 3{\cdot}162 \text{ seconds.}$$

Second stone : It is given that the second stone is thrown 1 second later and since both the stones hit the ground at the same time, the time taken (t_2) by the second stone to fall through the height of the cliff 49 m is given as

$$t_2 = 3{\cdot}162 - 1 = 2{\cdot}162 \text{ seconds}$$

Let u_2 = Initial velocity of the second stone

Again, $S = u_2 t_2 + \frac{1}{2} g t_2^2$

$$\text{or } 49 = u_2 \times 2{\cdot}162 + \frac{1}{2} \times 9{\cdot}8 \times (2{\cdot}162)^2$$

$$\text{or } u_2 = \boxed{12{\cdot}07\ m/s}$$

The second stone is thrown vertically downwards with a velocity of 12·07 m/s.

Example 10: (a) What is the mass of an object whose weight is 49 Newton? ($g = 9{\cdot}8\ m/s^2$)

(b) How much would a 65 kg man weigh on (i) the moon (ii) the earth? Given acceleration due to gravity of the earth $g_{earth} = 9{\cdot}8\ ms^{-2}$ and of the moon $g_{moon} = 1{\cdot}63\ ms^{-2}$.

(c) What would be his mas on the earth and on the moon ?

Solution : (a) mass of an object $= m = ?$

Weight of the object $= W = 49$ newton

Acceleration due to gravity of the earth

$$= g = 9{\cdot}8\ m/s^2$$

Since, Weight of an object $W = mg$

$$\therefore \quad m = \frac{W}{g} = \frac{49}{9{\cdot}8} \text{ kg}$$

$$= \boxed{5 \text{ kg}}$$

(b) Given, mass of the man = m = 65 kg

Acceleration due to gravity of the earth

$$= g_{earth} = 9{\cdot}8\ ms^{-2}$$

Acceleration due to gravity of the moon

$$= g_{moon} = 1{\cdot}63\ ms^{-2}$$

(i) Weight of the man on the moon

$$= mg_{moon}$$

$$= 65 \times 1{\cdot}63 \text{ newton}$$

$$= \boxed{105{\cdot}95 \text{ newton}}$$

(ii) Weight of the man on the earth $= mg_{earth}$

$$= 65 \times 9{\cdot}8 \text{ newton}$$

$$= \boxed{637 \text{ newton}}$$

(c) Since the mass of a body remains constant, the mass of the man remains 65 kg on the earth as well as on the moon.

Example 11: The earth's gravitational force causes an acceleration of 5 m/s^2 in a 1 kg mass somewhere in space. How much will the acceleration of a 3 kg mass be at the same place?

Solution: Since the acceleration due to gravitational force is independent of the mass of the body in which the acceleration is produced, so at the same place the acceleration of a 3 kg mass will be the same as that of a 1 kg mass. In other words the acceleration of a 3 kg mass at the same place will also be 5m/s².

Example 12: If a body weighs 60 kg on earth, how far must it go from the centre of the earth so that it weighs 30 kg? Radius of the earth = $6{\cdot}4 \times 10^6$ m.

Solution : The weight (W_1) of a body on the surface of the earth of radius R is given by

$$W_1 = \frac{GM_m}{R^2} \qquad ...(1)$$

where G is the gravitational constant; M is the mass of the earth and m is the mass of the body.

The weight (W_2) of the *same* body at a distance r from the centre of the earth and above the earth's surface is given by

$$W_2 = \frac{GM_m}{r^2} \qquad ...(2)$$

Dividing (1) by (2), we have

$$\frac{W_1}{W_2} = \frac{r^2}{R^2}$$

or
$$\frac{r}{R} = \sqrt{\frac{W_1}{W_2}}$$

or
$$r = R\sqrt{\frac{W_1}{W_2}}$$

Now $W_1 = 60 \times 9.8$ N; $W_2 = 30 \times 9.8$ N

and $R = 6{\cdot}4 \times 10^6$ m

$$\therefore\ r = 6{\cdot}4 \times 10^6 \sqrt{\frac{60}{30}}$$

$$= \boxed{9{\cdot}05 \times 10^6 \text{ m}}$$

Example 13: A ball is thrown vertically upward from the top of a bridge and falls into the water directly below the bridge 8·00 seconds later (i) How high did the ball go above the bridge, and (ii) how high is the bridge if the initial speed of the ball is 20·0 m/s? Neglect air resistance (Take g = 9.8 m/s²)

Solution : (i) Initial velocity of the ball = u = 20·0 m/s

Acceleration due to gravity = $-g = -9{\cdot}8$ m/s² (as g acts downwards)

Final velocity = $v = 0$ as the ball comes momentarily to rest at the top of its flight.

Vertical distance = $S = h = ?$

Since, $2\,a\,S = v^2 - u^2$

$\therefore\ 2\,(-g)\,h = v^2 - u^2$

or $2\,(-9{\cdot}8)\,h = (0)^2 - (20)^2$

$$\therefore\ h = \frac{400}{2 \times 9{\cdot}8} = \boxed{20{\cdot}4 \text{ m}}$$

(ii) Initial velocity of the ball = u = 20·0 m/s

Total time of flight = t = 8·00 second

Acceleration due to gravity = $-g = -9{\cdot}8$ m/s²

Vertical distance = $S = h = ?$

Note that the ***displacement*** is a ***vector quantity*** measured from the origin to the terminal point of the path. In this case the origin of the motion was the top of the bridge and the terminal point was the water below the bridge. Therefore, the displacement magnitude is merely the height of the bridge, even though the ball was initially thrown upward to a position 20·4 m above the bridge (Fig. 3·27). We need not consider the distance that the stone travels because the equations of motion *relate vector quantities.*

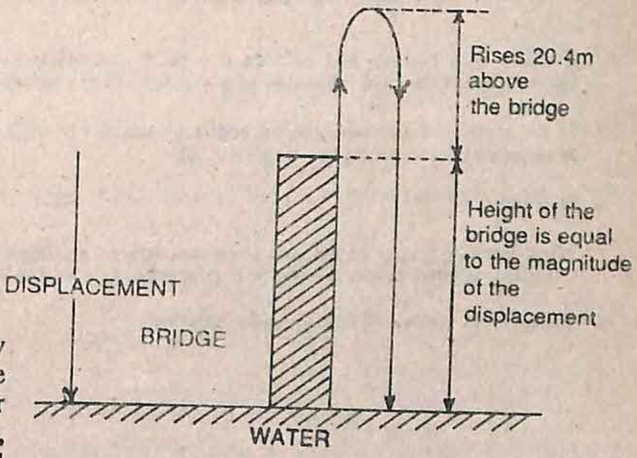

Rises 20.4m above the bridge
Height of the bridge is equal to the magnitude of the displacement
DISPLACEMENT
BRIDGE
WATER

fig. 3.27

Since, $S = ut + \frac{1}{2}gt^2$

$$\therefore\ h = (20{\cdot}0) \times 8 + \frac{1}{2}\,(-9{\cdot}8)\,(8)^2$$

$$= \boxed{-\ 154\ \text{m}}$$

The *minus sign* indicates that the displacement is down.

SUMMARY

1. **Gravitation (or force of gravitation):**

Every particle of matter in this universe attracts every other particle with a certain force in the direction of the line joining their centres. This force of universal attraction is known as gravitation.

2. **Newton's Law of Gravitation:**

Every body in this universe attracts every other body with a force which varies directly as the product of their masses and inversely as the square of the distance between their centres. The direction of force is along the line joining the centres of the two bodies.

Mathematically we can express this law as:

$$F = \frac{G\,m_1\,m_2}{r^2}$$

where $G = 6{\cdot}67 \times 10^{-11}\ \text{N m}^2/\text{kg}^2$

3. **Gravity of the earth:**

It is the force of attraction between the earth and the body lying on or near the surface of the earth.

4. **Acceleration due to gravity (g):**

It is the acceleration produced in a body due to the force of gravity.

$g = \frac{G\,M}{R^2} = 9.8\ \text{m/s}^2$ **where M is the mass of the earth having radius R.**

It varies with latitude and altitude at a place. Outside the earth, the value of g decreases with an increase in the distance. Inside the earth, the value of g decreases as we go towards its centre where its value is zero.

5. In the absence of air resistance, all bodies irrespective of their masses fall at the same rate *i. e.*, all bodies fall with the same constant acceleration due to gravity (g).

6. **Free fall:**

When force of gravity is the *only* force that acts on an object, we say that the object is in a state of *free fall*. To say something is freely falling is to say it is falling free of opposing forces of any kind, usually air resistance.

7. **Equations of motion of a body under gravity:**

$$v = u + gt$$

$$S = ut + \frac{1}{2}\,gt^2$$

$$v^2 - u^2 = 2\,gS \text{ where } g = 9{\cdot}8\ \text{m/s}^2.$$

Here S is the vertical distance, u is the initial velocity of the body; v is the final velocity of the body and t is the time taken. The acceleration due to gravity (g) is taken as *positive* for a body falling freely under gravity and *negative* for a body thrown vertically upwards.

8. **Weight of a body:**

It is a force with which a body is attracted by the earth.

Weight of a body = mg, where m is the mass of the body and g is the acceleration due to gravity.

9. **Distinction between mass and weight:**

Mass	*Weight*
(i) It is the quantity of matter in a body.	(i) It is the pull of the earth on a body.
(ii) Masses are compared by physical balances.	(ii) Weights are measured by spring balances.
(iii) It is a scalar quantity.	(iii) It is a vector quantity.
(iv) Mass of a body does not change from place to place.	(iv) Weight of a body changes from one place to another.
(v) Mass (m) = $\frac{F}{a}$ or $\frac{W}{g}$	(v) Weight (W) = mg
(vi) Its unit is kilogram (kg).	(vi) Its unit is *newton* (N).

10. A **projectile** is a body, which after having been given an initial velocity is allowed to move under the influence of gravity alone.

The horizontal and vertical motions of a projectile are independent of each other.

The path of a projectile is called its **trajectory.**

11. A body orbiting a planet is called its satellite.

Moon is the natural satellite of earth. It is constantly falling towards the earth. It does not hit the earth because the earth's surface curves away by the same amount.

QUESTIONS

[A] Objective Type Questions:

1. If the distance between two objects of constant mass is doubled, the gravitational force between them becomes

(a) one-fourth as great (b) one-half as great

(c) twice as great (d) four times as great .

2. A 20 kg mass is raised 5 m above the floor. Its weight, in newtons, is ....

3. As a distant meteor approaches a planet with no atmosphere, its acceleration towards the planet ....

4. When a kilogram of stainless steel is taken from sea level to the top of the Mount Everest, the weight of the stainless steel ...... but its mass ....

5. If the mass of one of two objects is doubled while the distance between them is also doubled, the gravitational force between them becomes ...... as great.

6. The force of attraction between two bodies does not depend on

(a) their separation
(b) the product of their masses
(c) the sum of their masses
(d) the gravitational constant.

7. Newton's Law of Gravitation

(a) can be verified in the laboratory
(b) cannot be verified but is true
(c) is valid only on earth
(d) is valid only in the solar system.

8. If a planet existed whose mass was *twice* that of the earth and whose radius 3 *times greater*, a 10 kg mass on its surface would weigh

(a) 2·2 newton
(b) 4·4 newton
(c) 6·7 newton
(d) 13·3 newton

9. When a space-ship is at a distance equal to two earth's radii from the centre of the earth, its gravitational acceleration is

(a) $19{\cdot}6\ m/s^2$
(b) $9{\cdot}8\ m/s^2$
(c) $4{\cdot}9\ m/s^2$
(d) $2{\cdot}45\ m/s^2$

10. If a planet existed whose mass and radius were both half those of the earth, the acceleration due to gravity at its surface would be

(a) $19{\cdot}6\ ms^{-2}$
(b) $9{\cdot}8\ ms^{-2}$
(c) $4{\cdot}9\ ms^{-2}$
(d) $2{\cdot}45\ ms^{-2}$

11. The acceleration due to gravity

(a) has the same value everywhere in space
(b) has the same value everywhere on the earth
(c) varies with the latitude on the earth
(d) is greater on the moon due to its smaller diameter.

12. The weight of an object

(a) is the gravity of the matter it contains.
(b) refers to its inertia.
(c) is the same as its mass but expressed in different units.
(d) is the force with which it is attracted to the earth.

13. A stone is dropped from a cliff. Its speed after it has fallen 100 m is

(a) 9·8 m/s (b) 44·2 m/s

(c) 19·6 m/s (d) 98 m/s

14. A ball is thrown up and attains a maximum height of 100 m. Its initial velocity was

(a) 9·8 m/s (b) 44·2 m/s

(c) 19·6 m/s (d) 98 m/s

15. A stone dropped from the roof of a building takes 4 seconds to reach the ground. The height of the building is

(a) 19·6 m (b) 39·2 m

(c) 156·8 m (d) 78·4 m

16. When an object is thrown up, the force of gravity

(a) is opposite to the direction of motion

(b) is in the same direction as the direction of motion

(c) decreases as it rises up

(d) increases as it rises up

17. In vacuum all freely falling bodies

(a) have the same speed (b) have the same velocity

(c) have the same acceleration (d) have the same force.

18. A woman with a normal weight of 500 N stands on a spring balance in an elevator which is accelerating upward with an acceleration of 3·0 m/s^2. The apparent weight of the woman, as read from the spring scale is :

(a) 500 N (b) 350 N

(c) 650 N (d) 0

(e) None of the above.

[**Hints:** R-mg = ma where R is the apparent weight]

19. Are these statements true ?

(a) Gravity is the attraction of mass for all other mass.

(b) Gravity acts over long distances, through empty space and through matter.

(c) The force of gravity pulls any two masses directly toward each other.

[B] Very Short Answer Type Questions:

1. How are mass and weight related ?
2. What is the weight of a one-kilogram box ?
3. State Newton's law of gravitation.
4. To what part of the universe does Newton's law of gravitation seem to apply ?
5. How does the gravitational pull depend on the distance between objects ?
6. Is the value of the gravitational constant same anywhere in this universe?
7. What is the value of G in S I units ?
8. The earth exerts a force of 9·8 N on a mass of 1 kg on earth. How much force will a mass of 500 g experience on earth?
9. Is it true that the value of g *i.e.*,acceleration due to gravity is the same for all planets?
10. An object of mass 5 kg falls freely with an acceleration of 9·8 m/s^2. What will be the acceleration of a freely falling object of mass 30 kg ?
11. State the SI unit of weight of a body.
12. State the SI unit of gravitational constant (G).
13. State the SI unit of mass of an object.
14. State the SI unit of acceleration due to gravity on the moon.
15. The earth attracts a body with a force of 8 N. With what force does this body attract the earth?
16. A book has a mass of 2 kg. What is the *net* force on it when you hold it in your palm? What is the force on it when it is released?
17. A satellite in orbit round the earth is an example of a freely falling body. Is it true or false?
18. Define gravitational constant.
19. Define acceleration due to gravity on earth.
20. Define free fall of a body. Or

    When is the body said to be falling freely?

[C] Short Answer Type and Essay Type Questions

1. What did Galileo discover in his legendary experiment on the Leaning Tower?
2. What exactly is meant by a *"freely falling"* object?
3. What is the gain in speed per second for a freely falling object?

4. If there is an attractive force between all objects, why do we not feel ourselves gravitating toward massive buildings in our vicinity?

5. By how much does the gravitational force between two objects decrease when the distance between them is doubled ? Tripled ? Increased tenfold? What will happen to the force when the distance is halved?

6. Consider an apple at the top of a tree that is pulled by earth gravity with a force of 1 N. If the tree were twice as tall, would the force of gravity be only $\frac{1}{4}$ as strong? Defend your answer.

7. In what sense is being infinitely far away from all celestial bodies like stepping off a table?

   [**Hints** : In both cases you would experience *weightlessness*. Far from celestial bodies you would be weightless in the strict sense, for you would be away from all gravitational influences; stepping from a table, you would momentarily experience apparent weightlessness because there would be a momentary lapse of support force.]

8. State Newton's law of gravitation and hence define universal gravitational constant G. State its SI unit. Why is the law called universal?

9. What is the magnitude of the gravitational force between the earth and your body?

10. What is the magnitude of the gravitational force between the earth and a 1 kg mass?

11. In Newton's thinking, what was the direction of force on a planet?

12. In Newton's insight, what did a falling apple have in common with the moon?

13. How can the moon "fall" without getting closer to the earth?

14. How does the force of gravity between two objects depend on their masses?

15. How does the force of gravity depend on the distance between two objects ?

16. Define weight of a body. State its S I unit.

17. Distinguish between: (i) *weight* and *mass* of a body (ii) Inertial mass and gravitational mass.

18. Define acceleration due to gravity of a body on a planet? What is its magnitude on earth? State its SI unit.

19. If the sun were twice as massive, would its pull on earth be twice as large? Would the earth's pull on it then be twice as large?

20. Do you think you would weigh more or less on the top of Mt. Everest that you do at home? Why?

21. If the mass of the earth remained constant but it began to shrink, what do you think would happen to the value of g? Is g larger at the equator or the poles?

22. Earth and the moon exert equal but opposite gravitational pulls on each other. Is it true or false ? Why ?

23. When a bullet is fired horizontally from a rifle, does it begin to fall as soon as it leaves the barrel? Or does air friction have to slow it so it will fall ?

24. A large asteroid collides with the moon, adding its mass to the moon's. Does earth's force of gravity on the moon increase ?

25. Why a shoe and a coin, dropped simultaneously from shoulder height, accelerate toward the ground at the same rate ?

[**Hints:** The net force on both the shoe and the coin is essentially the pull of gravity. On their way to the ground, they never move fast enough for air drag to become a factor.]

26. What is meant by *weightlessness*? Give an example.

27. What is a projectile? Give two examples of a projectile. Mention the expression for the vertical distance travelled by a projectile in time t.

28. What is an earth's satellite ? Why does it not fall to the earth ?

29. Deduce an expression for the acceleration due to gravity (g) for a body falling freely under earth's gravity. Hence, show that the value of g is independent of the mass of the falling body.

30. A body of mass m is falling freely on earth. The mass of the earth is M. Show that the acceleration with which the earth rises *towards* the body is given by

$$a_{earth} = \frac{m}{M} g$$

where g is the acceleration of the freely falling body.

31. How is the law of gravitation used for the measurement of mass ?

32. Using Newton's law of gravitation, calculate the vertical distance the moon falls in 3 days. Check your result by making a scale drawing choosing a convenient scale.

33. Explain why 10 kg stone will fall with the same acceleration as 1 kg stone ?

34. Will an object have a different inertia in the weightlessness of space ?

35. A person might weigh 700 newtons on earth, travels to the moon in an almost weightless condition and on arrival at the moon finds that his weight is less than 120 newtons.

(a) What is the meaning of the term weight ?

(b) Although the weight of the person might change, he possesses a property which will not change. What is that ?

36. Give an experiment to demonstrate that if two objects of different masses are released simultaneously from the same height, they will reach the ground at the same time. Neglect air resistance.

37. (a) What is gravitation ?

(b) State Newton's law of gravitation and hence define gravity and gravitational constant.

(c) What is the value of G in SI system ?

(d) What is the relationship between acceleration due to gravity and gravitational constant ?

38. Do you think the weight of a body will be the same everywhere on the Earth's surface ? Will it be the same if we go up a mountain or down a coal mine ? On the moon ? Way out in space?

Would your force-weighing apparatus be any use in these other places ? If not what other sort of apparatus would you have to take with you on a space journey to be able to measure forces ?

39. Why does a body become *weightless* ? Would it be pleasant to be weightless ?

PROBLEMS

1. What will be the weight of a body which has a mass of 5 kg ? ($g = 9{\cdot}8\ m/s^2$) **[Ans.** 49 N]

2. Two spheres with masses of 5 kg and 10 kg respectively are 0·300 metre apart. Calculate the force of attraction between them. ($G = 6{\cdot}67 \times 10^{-11}\ Nm^2/kg^2$) **[Ans.** $3{\cdot}705 \times 10^{-8}$N]

3. A 70 kg boy stands 1 m away from a 60 kg boy. Calculate the force of attraction between them. ($G = 6{\cdot}66 \times 10^{-11}\ Nm^2/kg^2$) **[Ans.** $2{\cdot}7972 \times 10^{-7}$ N]

4. Suppose you are 10^{12} km from a certain star and observe that the force of attraction between your spaceship and the star is 50 N. What will be the force when the distance of the star is reduced to 10^9 km ? **[Ans.** 5×10^{-7} N]

5. Calculate the mass of the earth from the following data:

$$g = 9{\cdot}8\ m/s^2$$
$$G = 6{\cdot}67 \times 10^{-11}\ N\,m^2/kg^2$$
$$R = 6{\cdot}34 \times 10^6\ m$$

Here 'g' is acceleration due to gravity, G is the gravitational constant and R is the radius of the earth. **[Ans:.** 60×10^{23} kg]

6. What will be the value of acceleration due to gravity at a place where a mass of 10 kg has a weight of 7·5 kg wt ? (1 kg wt ≈ 9·8 N) **[Ans.** 7·5 ms^{-2}]

7. Calculate the force of gravity due to the earth on a 40 kg boy standing on the ground. Mass of the earth = 6×10^{24} kg and radius of the earth = $6{\cdot}4 \times 10^3$ km. **[Ans.** 400 N]

8. Hydrogen atom, which is the simplest structure of all atoms, consists of an *electron* of mass $9{\cdot}1 \times 10^{-31}$ kg and a *proton* of mass $1{\cdot}7 \times 10^{-27}$ kg separated by an average distance of $5{\cdot}3 \times 10^{-11}$ m. Compute the gravitational force between them. $G = 6{\cdot}67 \times 10^{-11}\ Nm^2/kg^2$. **[An. :** $3{\cdot}67 \times 10^{-47}$ N]

9. A man has a mass of 70 kg on earth. What is his weight ? What are his mass and weight on the moon? Take $g = 10\ ms^{-2}$ on earth and $g = 1{\cdot}7\ ms^{-2}$ on the moon (*i.e.*, $\frac{1}{6}$th that on the earth).

[Ans. 700 N, 70 kg; 119 N]

10. A passenger in a stationary lift observes that an object hanging from a spring balance weighs 8 N. Later, when the lift is in motion, the reading on the spring balance is 6·8 N. Describe the motion of the lift at that moment.

If the object had been on a physical balance originally what would have happened when the lift started to move as above? [**Ans.** 1·5 m/s^2 downward]

11. A rock is dropped from the top of a 35·0 m building. (a) How long does it take to reach the ground? (b) What is the speed of the rock as it strikes the ground? [**Ans.** (a) 2·67 second (b) 26·2 ms^{-1}]

12. While over enemy lines in his balloon, a soldier throws a bomb vertically downward with an initial speed of 12·0 m/s from a height of 1250 m. (a) What is the speed of the bomb as it strikes the ground? (b) How long does it take the bomb to reach the ground? [**Ans:** (a) 157 m/s (b) 14·8 second]

13. A ball is thrown straight downward from a tower and hits the ground below exactly 2·50 second later. (i) How high is the tower, and (ii) What is the speed of the ball just before impact if its initial downward speed is 8·00 m/s? [**Ans.** (i) 50·7 m (ii) 32·5 m/s]

14. A bomber in a vertical dive at 60·0 m/s releases a bomb that strikes the ground 18·0 second later. (a) What is the speed of the bomb just before it strikes the ground? (b) From what height was the bomb released? [**Ans.** (a) 237 m/s (b) 2670 m]

15. A bullet fired vertically upward reaches a height of 2500 m. (a) What was its initial speed? (b) How long does it take to reach the height of 2500 m? [**Ans.** (a) 221 m/s (b) 22·6 second]

16. A rock is thrown vertically downward, into a lake, with an initial speed of 75·0 km/h from the top of a 135 m cliff. (a) How long does it take to reach the water? (b) What is the speed of the rock as it strikes the water? [**Ans.** (a) 3·54 second (b) 55·5 m/s]

17. A ball is thrown vertically upward with an initial speed of 32·0 m/s. (a) How high will it go? (b) How long will it take to return to the ground? (c) What is its speed as it strikes the ground?

[**Ans.** (a) 52·24 m (b) 6·53 second (c) 32 ms^{-1}]

18. A stone is dropped from a cliff into the sea below. (i) How long does the fall last, and (ii) What is the speed of the stone as it strikes the water if the cliff is 35·0 m high? Neglect air resistance.

[**Ans.** (i) 2·67 second (ii) 26·2 m/s]

19. What is the mass of a woman whose weight at the earth's surface is 525 N? ($g = 9{\cdot}81\ m/s^2$)

[**Ans.** 53·5 kg]

20. At the instant of blast off from the earth's surface, determine the acceleration of a rocket if its mass is $2{\cdot}82 \times 10^6$ kg and the total upward thrust (force) developed by its five engines is $3{\cdot}50 \times 10^7$ N. ($g = 9{\cdot}81\ m/s^{-2}$). (**Hints** : $F - mg = ma$) [**Ans.** 2·60 m/s^2 upward]

21. Suppose a planet existed whose mass was three times that of the earth and radius four times that of the earth (i) What would be the weight of a mass of 160 kg on that planet? (ii) What would be its mass on that planet? [**Ans:** (i) 30 N (ii) 160 kg]

22. (a) What is the force exerted on a freely falling ball, which has a mass of 2·0 kg, by the gravitational attraction of the earth?

    (b) What reaction force is exerted on the earth by the ball?

    (c) What acceleration of the earth would this force produce?

    (Mass of the earth = $5{\cdot}98 \times 10^{24}$ kg; $g = 9{\cdot}8\ m/s^2$). [**Ans.** (a) 19·6 N (b) 19·6 N (c) $3{\cdot}2 \times 10^{-24}\ m/s^2$]

□□

CHAPTER — 4

SIMPLE PENDULUM AND RESTORING FORCE

LEARNING OBJECTIVES

At the completion of this Chapter, you should be able to grasp :

(*i*) The concept of oscillatory motion and the meaning of periodic motion with examples from everyday life.

(*ii*) The meaning of simple pendulum ; oscillation (or vibration) ; time period ; frequency ; amplitude & length of simple pendulum.

(*iii*) The study of graphs between (a) Land T and (b) Land T^2 of a simple pendulum where L is the length of simple pendulum and T is its time period.

(*iv*) The meaning of restoring force and the origin of restoring force in a simple pendulum.

(*v*) The meaning of damped oscillations.

4.1. INTRODUCTION

In Chapter 1 we studied the motion of a body moving with constant speed in a straight line. We learnt to find the distance travelled by such a body in any given time. We then observed that bodies rarely move at the same speed. They change their speed or direction of motion due to the forces acting on them. We then learnt that an unbalanced force acting on a material body produced acceleration. This led us to study the motion of accelerated bodies. Motion in a straight line (*i.e.*, rectilinear motion) with constant speed and constant acceleration is not the only kind of motion we come across in daily life. There is a kind of motion of a body due to which the body moves to and fro about its rest (or mean) position. Such a motion is called **oscillatory motion,** *e.g.*, the motion of a child in a swing ; the motion of the piston of a steam engine ; the motion of the pendulum of a wall-clock. Let us now study a type of motion that repeats itself that is **periodic motion**. It is an oscillatory motion that repeats itself at regular intervals of time. A vibratory simple pendulum executes this type of motion. In this Chapter we shall study in some details the periodic motion of a simple pendulum.

4.2. THE SIMPLE PENDULUM

An ideal **simple pendulum** consists of a heavy particle or a small heavy spherical ball suspended by a long, weightless, inextensible and perfectly flexible string from a point about which it can oscillate without friction. But as these conditions cannot be achieved in practice, a metallic ball suspended by a fine cotton thread constitutes a simple pendulum.

Take a small heavy metallic sphere or a small stone or a pebble and tie it to one end of a string of a length of about one metre. Suspend the string as shown in Fig. *4·1* so that the metallic sphere or stone or pebble is free to swing. We now have a simple pendulum. The metallic sphere or the stone or the pebble is called the *bob* of the simple pendulum. The position O where the simple pendulum rests is called the *mean position* or the *rest position* of the simple pendulum (Fig. *4.1*).

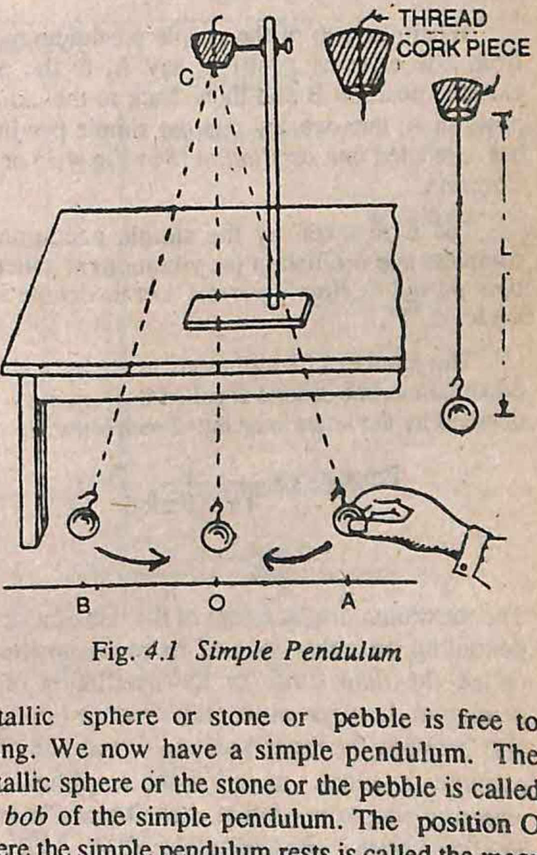


Fig. *4.1 Simple Pendulum*

If the simple pendulum whose position of rest is CO (Fig. *4.1*) is slightly displaced to position CA keeping the string taut and then let go, we will observe that the bob begins to move towards the mean position O as shown by the arrow. It does not stop at the mean position O due to the inertia of motion but it swings to position CB. At B it reverses its direction and begins to move towards the mean position O as indicated by the arrow. It crosses the mean position O and reaches the extreme position A where it again reverses it direction and begins to repeat the motion. Thus the bob of the simple pendulum keeps moving *to and fro* between two extreme positions A and B about the mean position O. *Such a to and fro motion which repeats itself is called* **oscillatory motion.**

The *length of simple pendulum* is the distance from the point of suspension about which the pendulum pivots to the centre of mass of the bob. Let us denote it by 'L' (Fig. *4.1*).

When the bob of the simple pendulum moves from one extreme position, say A, to the other extreme position B and then back to the extreme position A, then we say that the simple pendulum has executed *one oscillation* (See Fig. *4.1*) or *one vibration.*

The time taken by the simple pendulum to complete one oscillation (or vibration) is called its *time period* or simply *period*. Let us denote it by the letter 'T'.

The number of oscillations made by a simple pendulum in one second is called its *frequency*. It is denoted by the letter n or the Greek letter ϑ.

$$\text{Frequency} = \frac{1}{\text{Time Period}}$$

$$\vartheta = \frac{1}{T}$$

The maximum displacement of the bob of a simple pendulum on either side of its mean position is called the *amplitude* of the oscillation of the pendulum. In other words, the distance (along the arc) between the mean position O and one of the extreme positions is called the amplitude of a vibrating simple pendulum. Arc OA or OB is the amplitude of the simple pendulum (Fig. 4.1).

In order to make a detailed study of the motion of a simple pendulum, we need to measure the time it takes to complete one oscillation *i.e.*, its time-period T.

If we measure the time the simple pendulum takes to complete one vibration with the help of a stop-watch or a stop-clock, we will notice that this time is so small that it cannot be accurately determined. We should, therefore, measure the time for a large number of oscillations, say 30 oscillations and then divide this time by 30 to get the time for one oscillation, *i.e.*, its time-period T.

Activity

Let us take three objects such as a small stone or pebble, a small eraser and a small sphere of brass with a hook. Let us first make a simple pendulum having its length as 1 m with the pebble as its bob. Set this pendulum in oscillation and measure the time for 30 oscillations with a wrist-watch or a stop-watch. Let it be t. Then find $\frac{t}{30}$ which is the time for one complete oscillation, *i.e.*, its time-period, T. In other words $T = \frac{t}{30}$.

Repeat this activity with the eraser and the small sphere of brass instead of the pebble, *keeping the length of the pendulum the same in each case.* Fill in the following table :

Object at the end of the string	Time taken for 30 oscillations (t) in seconds	Time Period (T) is seconds $(T = \frac{t}{30})$
Pebble	....	....
Eraser	....	....
Brass sphere	....	....

Does the time taken for one oscillation change when the object tied at the end of the string is changed ?

We will find that the time-period (T) of the pendulum is the *same in each case*, *i.e.*, T does not depend on the mass of the bob of the simple pendulum. Thus, we conclude that *the time-period (T) of a simple pendulum does not depend on the mass of its bob.*

Let us now see if the time-period (T) of the simple pendulum depends on its length (L).

Activity

Make a simple pendulum by taking its length (L) as 80 cm and tying a pebble or a small brass sphere with a hook as its bob. With the help of a stop-watch, measure the time for 30 oscillations and then determine the time for one complete oscillation, *i.e.*, its time-period (T).

Use different lengths (L) of the pendulum with the *same bob* and measure the time-period (T) in each case. Fill in the table on next page for different lengths of the string, say L = 80, 90, 100, 110, 120, 130, 140 cm.

Length of the pendulum (L) (in cm)	Time for 30 oscillations (t) (in seconds)	Time-Period (T) in seconds ($T = \frac{t}{30}$)	T^2
80			
90			
100			
110			
120			
130			
140			

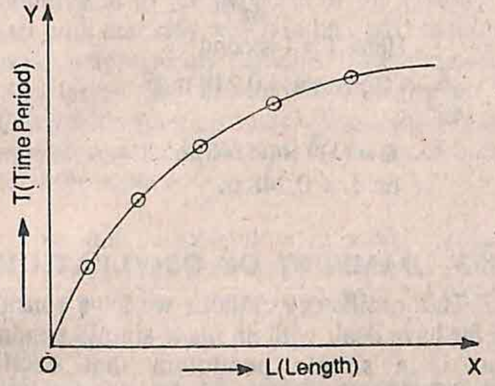


Fig. 4.2 *Graph between T and L*

What is the relation between L and T ? Let us plot a graph of the length of the pendulum L and its corresponding period T in the above activity. We will get a graph which looks like [Fig. 4.2]. What can you conclude from the graph ? This reminds us of the *parabola* which we studied at the end of Chapter 2-2 (Force and Acceleration). In such a graph, the length L and the period T are related by

$$L = \text{constant} \times T^2$$

or $$\frac{L}{T^2} = \text{constant.}$$

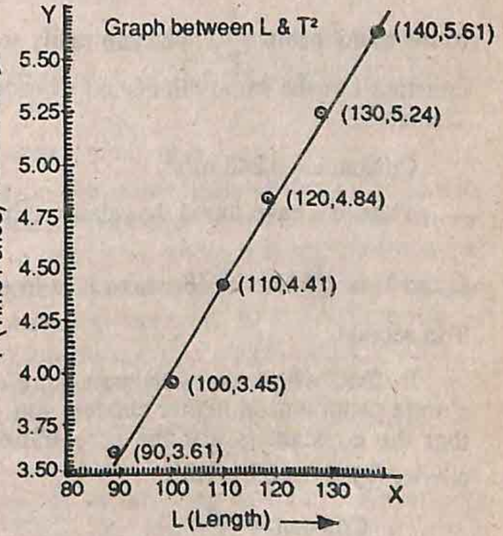


Fig. 4.3 *Graph between L and T^2*

What would a graph of L against T^2 look like ? We have seen a relationship of this sort before (Chapter 2-1). When an object moves with uniform speed, the relationship between the distance travelled and the time taken is exactly like the one above, that is,

$$\frac{\text{distance}}{\text{time}} = \text{constant speed}$$

Remember, the distance — $(\text{time})^2$ graph for such an object was a straight line. So let us plot a graph of L on the X-axis and T^2 on the Y-axis (Fig. 4.3). The straight line which is obtained confirms our guess that L and T are related by

$$L = \text{constant} \times T^2$$

$$\text{or} \quad \frac{L}{T^2} = \text{constant.}$$

We have to evaluate the constant. We could find the ratio from the observations that we have noted. The value of the constant is given by the *slope* of the straight line graph shown in Fig. 4.3. If you have performed this activity carefully you should get the following value for the constant :

Constant = 0.248.

What are the units of this constant ? If you go back to the relationship $\frac{L}{T^2}$, you can easily see that the constant has the same dimension as acceleration. Therefore,

Constant = 0.248 m/s^2

Thus, we have found the relationship between L and T as $\frac{L}{T^2} = 0.248$ where L is in metre and T in second.

In fact, when you will learn more about the simple pendulum in higher classes, you will find that the constant is just the acceleration due to gravity (g) divided by $4\pi^2$.

$$\text{Constant} = \frac{g}{4\pi^2}$$

In other words,

$$L = \frac{g}{4\pi^2} . T^2$$

$$\text{or } T = 2\pi\sqrt{\frac{L}{g}} \qquad \text{........ } (i)$$

The equation (*i*) gives the time-period (T) of a simple pendulum in terms of the length of the pendulum (L) and the acceleration due to gravity (g). From this relation we notice that

(*a*) the time period of a simple pendulum *does not depend* on the mass of its bob.

(*b*) the time-period of a simple pendulum is *directly* proportional to the square root of the length of the pendulum

$$T \alpha \sqrt{L}$$

$$\text{or } T^2 \alpha L$$

(c) the time-period of a simple pendulum is *inversely* proportional to the square root of the acceleration due to gravity (g).

Let us now find the length of a simple pendulum at a place (where $g = 9.8\ m/s^2$) whose time-period is 1 second.

From the relation

$$T = 2\pi\sqrt{\frac{L}{g}}, \text{ we have}$$

$$T^2 = 4\pi^2 . \frac{L}{g}$$

$$\text{or } L = T^2 . \frac{g}{4\pi^2}$$

Here, T = 1 second

$$\frac{g}{4\pi^2} = \text{Constant} = 0.248\ m/s^2$$

$$\therefore\ L = (1)^2 \times (0.248) m$$

$$\text{or } L = 0.248\ m.$$

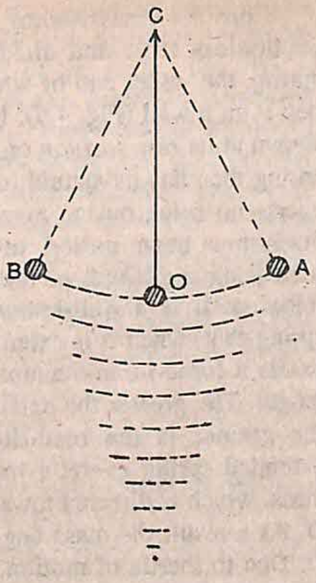
4.3 DAMPING OF OSCILLATIONS

The oscillatory motions we have considered so far have dealt with an *ideal* simple pendulum, that is a simple pendulum that oscillates indefinitely under the action of a restoring force. In a realistic simple pendulum, *dissipative forces*, such as friction, are present and retard the motion of the pendulum. Consequently the mechanical energy of the system will diminish in time, and the motion is said to be *damped*.

Damped oscillations are periodic oscillations with gradually decreasing amplitude.

The oscillations of a simple pendulum are damped oscillations (Fig. 4.4). The oscillations do not go on forever. The amplitude of oscillations gradually decreases until the body comes to rest.

The gradually decreasing amplitude indicates dissipation of energy. There are two main causes of the dissipation of energy : (1) forces of *internal friction*, called into play due to the relative displacement of the particles within the body progressively dissipate the energy. Thus gradual transformation of energy of vibration into heat takes place, (2) the oscillating body continuously transfers energy to the particles of the medium in which it is situated.



Damping of Oscillations
Fig. 4.4

In each oscillation, part of the energy is communicated to the particles of the medium in contact with the body which in turn pass that on to the other neighbouring particles. Thus the energy of oscillation is continuously dissipated by frictional and radiation losses. From the point of view of an oscillating system, the effect of both is to resist the motion.

If we put the pendulum in a big evacuated vessel or tube and, therefore, eliminate air friction, the pendulum will continue to oscillate for a longer time.

If, however, we immerse the pendulum in a jar containing a liquid, the oscillating pendulum would *quickly* come to rest. In fact, the time in which it comes to rest tells us the *extent of friction* exerted by the liquid. This method is sometimes used to find the frictional forces exerted by the liquid.

It is observed that a simple pendulum with a *small* and *heavy* bob will oscillate in air for a much larger time than a pendulum with a large and light bob because a small bob has a small surface area and hence would experience less frictional forces and a heavy bob has more inertia and, hence, would be more effective in resisting the force of friction.

4.4 RESTORING FORCE

Observe the oscillation of a simple pendulum (Fig. 4.1) and let us consider the force which is responsible for keeping a pendulum in oscillation. When the bob of the pendulum moves from its mean position O to one of the extreme positions, say A, then from A to O, from O to the other extreme position B and then back to the mean position O, we say that the pendulum executes one complete oscillation. Answer the following questions in connection with the four stages of one complete oscillation of the bob of the pendulum :

Does the speed of the bob of the pendulum increase or decrease as it goes from (1) O to A ? (2) A to O ? (3) O to B ? (4) B to O ?

Remember that a force acting in the direction opposite to that of motion decreases the speed. The slowing down of a ball thrown up is an example of this . On the other hand, when the force acts in the direction of motion, the speed of an object always increases. A ball speeding up when released from a height is an example of this.

What is the direction of the force responsible for the speeding up or slowing down of the bob as it oscillates ?

(*i*) *Motion from O to A :*

As the bob moves from O to A , its velocity gradually decreases from a maximum value at O to zero at A where it momentarily stops. Hence, an unbalanced force must be acting in a direction opposite to the direction of motion during this stage, *i.e.*, the force is directed towards the mean position O.

(*ii*) *Motion from A to O* :

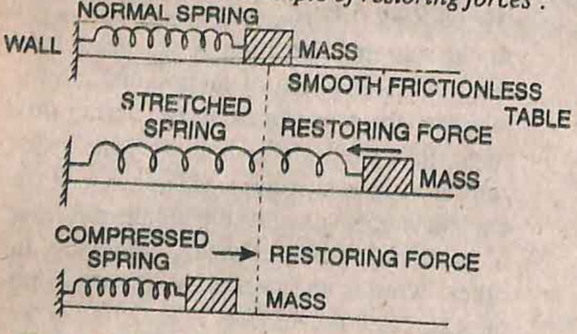
At the extreme position A the pendulum reverses its direction of motion and moves towards the mean position O. During this stage, the speed of the bob increases from zero at A to a maximum value at O. Since the bob is tracing a curved path, the direction of its motion is also changing constantly. In other words, the velocity of the bob increases as it moves from A to O. We know that the velocity of a body can change only if an unbalanced force acts on it. Hence during this stage also, the force acts towards the mean position because from A to O the velocity is gradually increasing.

(*iii*) *Motion from O to B :*
During this stage, the velocity of the bob gradually decreases until it reaches the extreme position B where its velocity is momentarily zero. Hence, an unbalanced force must be acting in a direction opposite to the direction of motion during this stage *i.e.*, the force is again directed towards the mean position O.

(*iv*) *Motion from B to O :*
At the extreme position B the bob of the pendulum reverses its direction of motion and moves towards the mean position O. During this stage the velocity of the bob gradually increases until it reaches O where its velocity is maximum. Hence, during this stage also, the unbalanced force is directed towards the mean position.

Thus, we find that the unbalanced force acting on the simple pendulum depends on the position of its bob. If the bob is to the right of the mean position O (Fig. 4.1), the unbalanced force acts to the left. When the bob is to the left of the mean position O, the unbalanced force acts to the right. Hence the velocity of the bob always increases when it moves towards the mean position O. The velocity decreases as it moves away from O. It is this unbalanced force which is responsible for keeping a simple pendulum in oscillation. *Such an unbalanced force which acts towards the centre or the mean position during an oscillatory motion is called the* **restoring force**.

Let us see *another example of restoring forces :*



(Fig. 4.5) [Oscillation of a mass due to a spring]

Consider a mass sliding on a perfectly smooth, frictionless table and attached to one end of a spring, the other end of which is held fixed by a peg P on a wall (Fig. 4.5). In Fig. 4.5 the mass is shown at its *rest position* or *mean position O*. The spring then has its natural, unextended length and exerts no force on the mass. In Fig. 4.5 (b) the mass has been pulled to the right, thereby, increasing the length of the spring and then it is released. It is a well-known characteristic of a spring that, when it is extended or compressed, it exerts a force in an attempt to retain its original length. The greater the extension or compression, the greater is the restoring force. Hence the extended spring exerts a restoring force on the mass which is directed towards the mean position O. As a result the mass begins to move towards O. Due to inertia of motion, the mass overshoots the mean position O and moves to the left until it reaches the extreme position B (Fig.4.5 (c)). At this position the spring is compressed and now it exerts a restoring force on the mass pushing it to the right in an attempt to regain its original length. In this case also, the restoring force is directed towards the mean position O.

Thus we find that if a mass attached with a horizontal spring is displaced from its original rest position or the mean position, *the system exerts a restoring force* on it which is in such a direction as to return it to its mean position. Hence it is this restoring force which keeps the mass in horizontal oscillation about its mean position.

If there were no frictional forces the oscillations caused by restoring forces would continue forever. However, as we saw earlier, a pendulum, ultimately comes to a stop due to friction. You may be familiar with a swing in a park which quickly stops if some force is not applied. Sometimes this slowing down is desirable. In a spring balance, for example, if the mass did not come to rest quickly, we would hardly be able to read its weight.

4.5 **WHY DOES THE PENDULUM OSCILLATE ? *(The Origin of Restoring Force)*

What is the origin of the restoring force in a simple pendulum ? Let us try to understand it. What would happen if the string of the pendulum cut, when the bob is at its mean position O ?

** For further knowledge only

Obviously, the mass at the end of the string would fall to the earth. This, we have learnt, is due to the gravitational attraction of the earth. The string, therefore, holds the bob at a height by balancing the attraction of the earth. Thus there are two forces acting on the pendulum. One is the gravitational attraction of the earth which pulls the bob towards the earth *i.e.*, weight = mg of the bob where m is the mass of the bob and g is acceleration due to gravity at a place on the earth. The second is the force exerted by the string along its length called *tension* (T) which prevents the bob from falling to the earth.

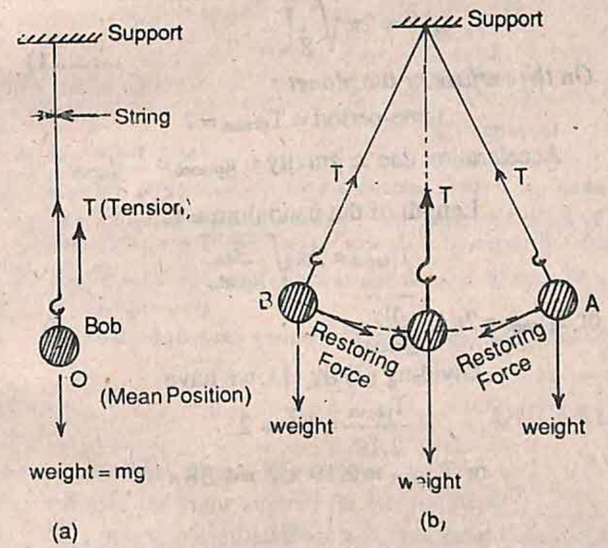


Fig. 4.6

When the bob is at its mean position O, the two force, *i.e.*, the weight of the bob and the tension in the string are balanced. Since these balanced forces cannot change the state of motion of the pendulum (*i.e.*, produce no acceleration) so the bob will remain at rest at O as shown in Fig. 4.6 (a).

However, when the bob is at an extreme position A, an unbalanced force acts on the bob and hence the bob begins to move towards O. What happens is that the tension (T) in the string can no longer compensate and balance the pull of the earth. The bob, therefore, falls but is kept at a fixed distance from the support by the string. The trajectory of the bob is, therefore, an arc of a circle as shown in Fig 9.6 (b).

When the bob falls and returns to the mean position O, the pull of the earth is again balanced by the string. That is, the total force on the bob is now zero. But unlike before, the bob is not at rest. It has a certain velocity. In the absence of any force at the mean position, the bob continues ahead due to inertia of motion with the same velocity and crosses over to the other side.

Once it crosses the mean position the string cannot balance the pull of the earth. Its velocity, therefore, decreases, until at the other extreme position B, its velocity is zero. It now begins its fall back to the earth exactly as it fell before, *i.e.*, as it did when it was at A. Each time it arrives at the mean position, it crosses over to the other side due to its inertia and the oscillations continue.

Thus we find that it is the combination of the two forces, the pull of the string (*i.e.*, its tension) and the pull of the earth that give rise to the restoring force, directed towards the mean position. This restoring force is responsible for keeping the simple pendulum in oscillation.

SOLVED EXAMPLES

Example 1.

What is the period of a pendulum of length 9. 8 metres ? ($g = 9.8\ m/s^2$)

Solution

Given

$L = 9.8$ m $g = 9.8\ m/s^2$

$T = ?$

Since,

$$T = 2\pi\sqrt{\frac{L}{g}}$$

$$\therefore T = 2\pi\sqrt{\frac{9.8}{9.8}} = 2\pi \text{ seconds}$$

$$= \mathbf{6.286 \text{ seconds}}$$

Example 2.

Second's pendulum is that simple pendulum whose length is such that it completes one oscillation in 2 seconds. Calculate the length of a second's pendulum at a place where $g = 9.\ 8\ m/s^2$.

Solution :

Given,

$T = 2$ seconds $g = 9.8\ m/s^2$

$L = ?$

We know that

$$T = 2\pi\sqrt{\frac{L}{g}}$$

$$\text{or } T^2 = 4\pi^2 . \frac{L}{g}$$

$$\text{or } L = \frac{T^2 g}{4\pi^2} = \frac{(2)^2 \times 9.8}{4 \times (\frac{22}{7})^2}$$

$$= 0.993 \text{ metre} = \mathbf{99.3 \text{ cm}}$$

Example 3.

A simple pendulum, of length 120 cm, completes 40 oscillations in 88 seconds at a place. Calculate the acceleration due to gravity at that place.

Solution :

Given, $L = 120 \text{ cm} = 1.20 \text{ m}$

$$T = \frac{88}{40} = 2.20 \text{ seconds}$$

$$g = ?$$

$$\text{Since, } T = 2\pi\sqrt{\frac{L}{g}}$$

$$\text{or } T^2 = 4\pi^2 . \frac{L}{g}$$

$$\therefore g = 4\pi^2 . \frac{L}{T^2}$$

$$= \frac{4 \times (3.142)^2 \times 1.20}{(2.20)^2}$$

$$= 9.79 \text{ m/s}^2$$

Example 4.

A simple pendulum has a time period of 2.19 s at a place on the surface of the earth. What will be its time-period if it were taken to a planet where the acceleration due to gravity is $\frac{1}{4}$ th that on the earth ?

Solution :

On the surface of the earth :

Time-period = $T_{earth} = 2.19$ s

Acceleration due to gravity = g_{earth}

Length of the pendulum = L

Since,

$$T_{earth} = 2\pi\sqrt{\frac{L}{g_{earth}}}$$

$$\therefore 2.19 = 2\pi\sqrt{\frac{L}{g_{earth}}} \qquad \text{........(1)}$$

On the surface of the planet :

Time-period = T_{planet} = ?

Acceleration due to gravity = $g_{planet} = \frac{1}{4} g_{earth}$

Length of the pendulum = L

$$\therefore T_{planet} = 2\pi\sqrt{\frac{L}{g_{planet}}}$$

$$\text{or } T_{planet} = 2\pi\sqrt{\frac{4L}{g_{earth}}} \qquad \text{.......(2)}$$

Dividing (2) by (1), we have

$$\frac{T_{planet}}{2.19} = \sqrt{4} = 2$$

$$\text{or } T_{planet} = 2.19 \times 2 = 4.38 \text{ s}$$

SUMMARY

1. *Simple pendulum :*

   It is a small and heavy bob (or body) suspended by a long weightless, inextensible and perfectly flexible string from a rigid support.

2. *Length of simple pendulum :*

   It is the distance between the point of suspension and the centre of mass of its bob.

3. *Mean position of a simple pendulum :*

   It is the rest position of the bob of a simple pendulum.

4. *Oscillation (or vibration) of a simple pendulum :*

   The motion of the bob of a simple pendulum from its mean position to one extreme position, then to the other extreme position and back to the mean position is called one complete oscillation (or vibration).

5. *Time-period :*

   It is the time taken by a simple pendulum to complete one full oscillation (or vibration).

6. *Amplitude of a simple pendulum :*

   It is the distance between the mean position and one of the extreme positions on either side of the mean position of an oscillating simple pendulum.

7. The time period of a simple pendulum is given by the relation :

$$T = 2\pi\sqrt{\frac{L}{g}}$$

where T = time-period

L = length of simple pendulum

and g = Acceleration due to gravity.

Hence it is clear from the above relationship that

(*i*) The time-period (T) of a simple pendulum is *independent* of the mass of its bob.

(*ii*) The time-period (T) of a simple pendulum is *directly proportional* to the square root of the length of the simple pendulum.

$$T \propto \sqrt{L}$$

$$\text{or } T^2 \propto L$$

$$\text{or } \frac{T^2}{L} = \text{constant.}$$

(*iii*) The time period (T) of a simple pendulum is *inversely proportional* to the square root of the value of the acceleration due to gravity.

$$T \propto \sqrt{\frac{1}{g}}$$

$$\text{or } T^2 \propto \frac{1}{g}$$

$$\textbf{or } T^2 g = \textbf{constant.}$$

8. *Restoring force* :

It is that force which is always directed towards the mean position of an oscillating simple pendulum.

The restoring force arises due to the combined effect of the gravitational attraction of the earth and the pull of the string (*i.e.*, the tension in the string). It is responsible for the oscillatory motion of a, simple pendulum.

9. The gradual decrease in the amplitude of oscillation of a simple pendulum due to dissipating forces such as friction is called *damping*.

Damped oscillations are periodic oscillations with gradually decreasing amplitude.

QUESTIONS

[A] Objective Type Questions :

Choose the right answers in the following :

1. The periodic oscillation of a simple pendulum can be significantly reduced by
   (*a*) increasing the mass of the pendulum bob
   (*b*) increasing the volume of the pendulum bob
   (*c*) decreasing the amplitude of swing of the pendulum
   (*d*) decreasing the length of the pendulum.
   (*e*) decreasing the atmospheric pressure acting on the bob.
2. The period of a simple pendulum depends on its
   (*a*) mass,
   (*b*) length,
   (*c*) amplitude,
   (*d*) energy.
3. The period of a simple pendulum whose length is 1 m is
   (*a*) about 2 seconds,
   (*b*) about 1 second,
   (*c*) about 9.8 seconds,
   (*d*) about 4.9 seconds.
4. If the length of the pendulum is doubled, the period of the pendulum
   (*a*) is halved,
   (*b*) is doubled,

(*c*) become four times,

(*d*) become one-fourth.

5. The period of a simple pendulum whose length is 9.8 m is

(*i*) 2π seconds,

(*ii*) 4π seconds,

(*iii*) $\pi/2$ seconds,

(*iv*) π seconds.

6. A simple pendulum is oscillating between extreme positions P and Q about the mean position O. The velocity of the pendulum bob will be maximum when it is

(*i*) at P

(*ii*) at Q

(*iii*) at O

(*iv*) midway between O and P.

(*v*) midway between O and Q.

7. The time-period (T) of a simple pendulum of length L is given by

$$T = \text{constant} \times \sqrt{L}$$

The constant stands for

(*i*) $\frac{4\pi}{\sqrt{g}}$

(*ii*) $\frac{2\pi}{\sqrt{g}}$

(*iii*) $\frac{g}{2\pi^2}$

(*iv*) $2\pi\sqrt{g}$

[B] Very Short Answer Type Questions

1. What is the period of a simple pendulum whose length is 9.8 m ?
2. The time-period of a simple pendulum is 2.0 seconds. How much time does it take to move from one extreme to the other extreme ?
3. The time period of a simple pendulum is 1·6 seconds. How much time does it take to move from its mean position to one extreme position ?
4. If the length of a simple pendulum is made four times, its time period also becomes four times. Is it true or false ?
5. A simple pendulum has a bob of mass 0.5 kg and its time-period is 2.0 seconds. What will be its time-period if the mass of its bob is increased to 0.6 kg ?
6. The time-period of a simple pendulum on the surface of the earth is 1.8 seconds. If the same simple pendulum is taken to the top of the Mount Everest, its motion will become faster. Is it true or false ?
7. Two pendulums have time-period in the ratio of 1 : 4. What is the ratio of their lengths ?
8. Name the force which is responsible for the oscillations of a simple pendulum.
9. What is the direction of the force responsible for the speeding up or slowing down of the bob of a simple pendulum as it oscillates ?
10. Does the speed of the bob of a simple pendulum increase or decrease as it goes from its

    (*i*) extreme position to the mean position ?
    and

    (*ii*) mean position to the extreme position ?
11. The distance between the two extreme positions of an oscillating simple pendulum is 1.2 cm. What is the amplitude of oscillation ?

[C] Short Answer Type and Essay Type Questions

1. What is a simple pendulum ?

2. Define : (i) an oscillation, (ii) time period and (iii) amplitude of an oscillating simple pendulum. State SI Unit of time-period.

3. Name the factors upon which the time-period of a simple pendulum depends.

4. When is the velocity of the bob of an oscillating pendulum : (i) maximum and (ii) zero ?

5. Why does the amplitude of a simple pendulum gradually decrease with time ?

6. What is damping ? What are damped oscillations ? What is damping due to ?

7. What is a restoring force ? Give two examples.

8. What is the value of the "constant" in the relation

$$T = \text{constant} \times \sqrt{L}$$

where T is the time-period of a simple pendulum of length L ?

*9. Why does the pendulum oscillate ?

OR

Explain the origin of the restoring force in an oscillating simple pendulum.

10. How will you obtain the relation between the length (L) and time period (T) of a simple pendulum ? What is the nature of the graph between (a) time-period and its length and (b) length and (time-period)^2?

11. What feature about a pendulum makes it useful in clocks ?

12. What is the period of a pendulum ?

13. If a pendulum takes one second to make a complete to and fro swing, how great is its period ?

14. The period of a certain pendulum is 2 s, and the period of another is 1 s. Which pendulum is longer ?

15. Will a pendulum clock that is accurate at sea level gain time or lose time when located high in the mountains ?

16. If a pendulum is shortened, does its frequency increase or decrease ? What about its period ?

17. You swing an empty suitcase to and fro at its natural frequency. If the suitcase were filled with books, would the natural frequency be lower, greater, or the same as before ?

18. How should a pendulum clock which loses time be adjusted ?

19. How could a pendulum be used to measure the value of g, the acceleration due to gravity at a place ?

PROBLEMS

1. Find the length of a pendulum which has a period of 1.00 s for a complete oscillation at a location where $g = 9.80 \text{ ms}^{-2}$.

[Ans. 0.248 m]

2. A pendulum 25 cm long describes 20 oscillations in 20.0 seconds. What is the period of a pendulum 1 m long ?

[Ans. 2 seconds]

3. What is the period of a pendulum 1.5 m long ? Use $g = 9.8 \text{ m/s}^2$.

[Ans. 24.6 seconds]

4. If a pendulum 1.0000 m long has a period of 2.0065 seconds at a place on the surface of the earth, what is the value of acceleration due to gravity in that location ?

[Ans. 9.81 m/s^2.]

5. The Standard Seconds Pendulum has a period of two seconds for a complete oscillation on the surface of the earth. What will be its time period if it is taken to the moon ? The acceleration due to gravity on the moon is $\frac{1}{6}$th of that on the earth.

[Ans. 4.9 s]

6. Two pendulums have time periods in the ratio of 1 : 2. What is the ratio of their lengths ?

[**Ans.** $\frac{1}{\sqrt{2}}$]

7. Find the length of a simple pendulum which will have the same time period on the moon as that of a pendulum of length 1 m on the earth. The value of acceleration due to gravity on moon = 1. 6 ms^{-2} and on earth = 9.8 ms^{-2}

[**Ans.** 16.3 cm]

8. Find the length of a simple pendulum whose time period is 2π seconds. Use g = 9.8 ms^2.

[**Ans.** 9.8 m]

□ □

CHAPTER — 5

WORK AND ENERGY

LEARNING OBJECTIVES

At the completion of this Chapter, you should be able to grasp :

(i) The concept of work done by a force and how is it measured ?

(ii) The concept of energy—kinetic energy and potential energy.

(iii) The relationship between work and energy.

(iv) The interchange of kinetic and potential energy.

(v) The law of conservation of energy.

(vi) The various forms of energy and transformation of energy.

(vii) The idea of escape velocity—it is obtained from the fact that potential energy gained by the body equals its loss of kinetic energy.

5.1 INTRODUCTION

In an earlier Chapter on Force and Acceleration, we saw that changes in an object's motion depend on both force and how long the force acts. "How long" meant time. We called the quantity "force × time" *impulse*. But "how long" need not always mean time. It can mean distance also. When we consider the quantity *force × distance*, we are talking about an entirely different quantity--**work.**

Perhaps the concept most central to all of science is *energy*. The combination of energy and matter makes up the universe : matter is a substance and energy is the mover of substance. The idea of matter is easy to grasp. Matter is stuff that we can see, smell and feel. It has mass and occupies space. Energy, on the other hand, is abstract. We cannot see, smell, or feel most forms of energy. Surprisingly, the idea of energy was unknown to Isaac Newton, and its existence was still being debated in the 1850s. Although energy is familiar to us, it is difficult to define, because it is not only a "thing" but both a thing and a process. Persons, places and things have energy but we usually observe energy *only when it is happening* — only when it is being transformed. It comes to us in the form of electromagnetic waves from the sun and we feel it as heat ; it is captured by plants and binds molecules of matter together ; it is in the food we eat and we receive it by digestion.

5.2 WORK AND ITS MEASUREMENT

Whenever a force is applied on a body and there is a change in shape, volume or position of the body, the force is said to have done work. Work is measured by the product of force and distance through which the point of application of the force moves in the direction of the force.

Thus work is done whenever the application of force produces a change. The change may be of any sort say a change in the position of an object. The change may be in the velocity of an object or the change could be in the shape of an object, its chemical composition, its temperature or even its colour. Every change involves work.

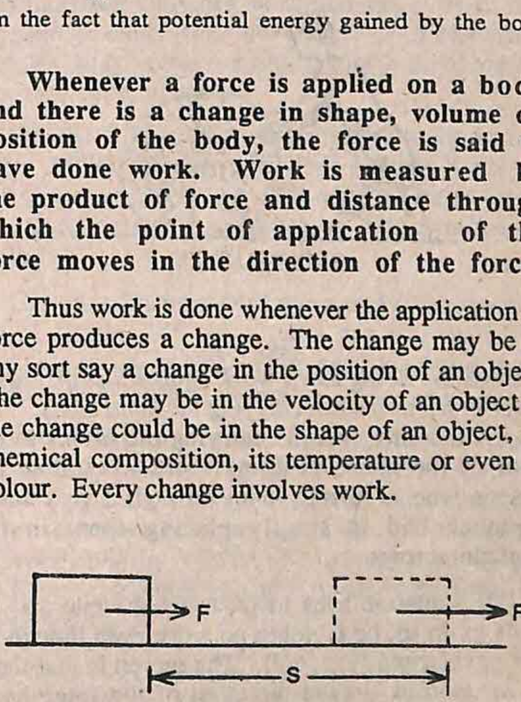


Fig. 5.1

If a force F moves a body through a distance S [Fig. 5.1] parallel to the line of action of the force, then work done W is given by

$$\boxed{W=F \times S} \quad ....(1)$$

If the point of application does not move any distance (direct or indirect) in the direction of the force, *no work is done*. Therefore, work in the scientific sense means an *achievement* and not a mere effort as used in daily language.

When we twist a wire and change its shape, work is done against internal forces of cohesion between the molecules of the wire. When we press a football bladder, we change its volume and work is done against the pressure of the gas in the bladder. When we push a cycle, we change its position and work is done against the force of friction between the wheels and their axles etc.

When a man is carrying a hand bag to the railway station and is walking on a level road, scientifically *he is doing no work* because the force that he is applying against the weight of the bag is vertically upwards and his motion is in the horizontal direction and there is no motion in the direction of the force he is applying. [*But here too this man is doing extra work against the increased force of friction when carrying the hand bag*.]

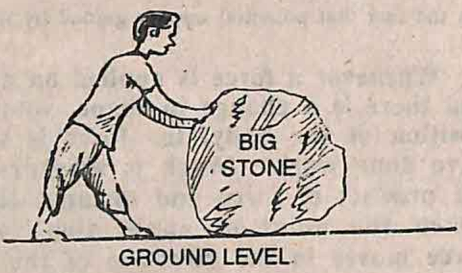


Fig. 5.2

A labourer, who is carrying the bricks to the roof of the house is doing more work than the mason who is raising them through a very small distance and is simply placing them in the horizontal rows.

If someone tries to push a big stone and he fails to do so, he is doing no work even though he gets exhausted (Fig. 5.2). The reason is that there is *no motion* in the direction of the force he is applying. Though he does no work *on* the stone yet work may be done on the muscles by stretching and contracting, which is force times distance on a biological scale, but this work is not done on the stone.

Thus the definition of work involves both a force and a displacement.

WORK DONE BY A FORCE ACTING OBLIQUELY ON OBJECTS :

Let us consider a case where the displacement may not occur in the direction of the force. For example, when a passenger on a railway platform pulls at a chain tied to a heavy suitcase, he applies a force along the direction of the chain, whereas the suitcase moves along the ground [Fig. 5.3 (a)]. To calculate the work done in this case consider a force $\vec{F}$ acting on the suitcase in a direction inclined at an angle say θ with the horizontal smooth surface along which the suitcase moves [Fig. 5.3 (a)]. Let $\vec{S}$ be the displacement of the suitcase along the surface as it moves from position P to position Q. In this case, work done by the force is not given by the simple product "force × distance" but it is calculated by two equivalent ways described as follows :

(i) You have learnt that displacement is a vector quantity *i.e.*, it has a magnitude as well as a direction. Again, force is also a vector quantity *i.e.*, it also has a magnitude as well as a direction. You have also learnt how to represent a vector. In Fig. 5.3 (b), vector $\overrightarrow{PQ}$ represents the displacement vector and vector $\overrightarrow{PL}$ represents the force vector, inclined to each other at an angle θ. To find the work done, we draw a perpendicular from the arrow- head of the displacement vector $\overrightarrow{PQ}$ on the force vector $\overrightarrow{PL}$ as shown in Fig. 5.3 (b). R is the foot of the perpendicular and the distance PR gives the distance moved in the direction of the force. In fact the distance PR is called the *projection* of vector $\overrightarrow{PQ}$ on vector $\overrightarrow{PL}$. Hence, in this case,

Workdone =	Magnitude of the force	×	Projection of the displacement vector on the force vector

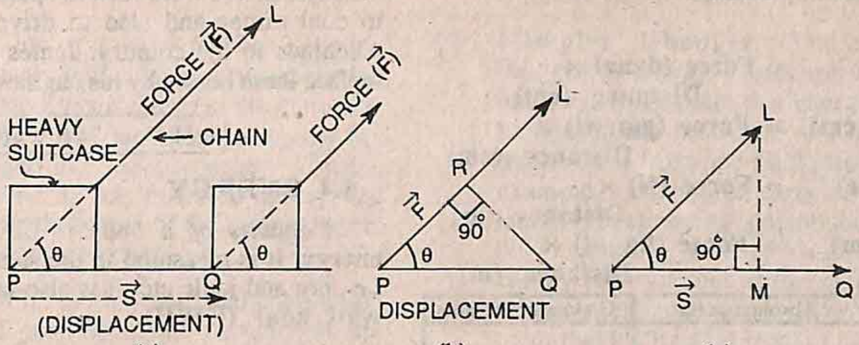
or $W = F \times PR$

(ii) The work done can also be calculated by considering the projection of the force vector $\overrightarrow{PL}$ on the displacement vector $\overrightarrow{PQ}$ as shown in Fig. 5.3 (c).

In this case,

Work done =	Magnitude of the displacement	×	Projection of the force vector on the displacement vector

or $W = S \times PM$



(a) (b) (c)

Fig. 5.3

Sometimes this way of calculating the work done is more convenient.

The work is evidently F.S when the body moves in the *same direction* in which the force is applied as θ is then zero. Work done is *zero* if the displacement of the body is at right angles to the force applied and θ =90°.

In this case the projection PM of the force vector $\vec{F}$ on the displacement vector is zero.

An artificial satellite going round the earth is an example of such motion. The artificial satellite is held to the earth by the force of gravity, which acts along the line joining the centres of the two. The satellite moves along the circumference of the circle *i.e.*, at right angles to the direction of the force. The earth going round the sun is another example of such a motion. Whirling of a stone tied to a string is also an example of this type of motion. The stone moves in a circular path and at every moment it is moving at right angle to the direction of force applied which is also the string.

It must be noted here that for doing work, two factors are involved, force and displacement and although force and displacement are both vector quantities but work which is measured by their product is a scalar quantity.

UNITS OF WORK

The unit of work is the amount of the work done when a unit force moves a body through a unit distance along its direction of application. Evidently, the unit of work depends upon the units of force and distance.

Absolute Units. In the C.G.S. System, the absolute unit of work is called **erg.** *It is the amount of work done when a force of one dyne moves a body through a distance of 1 cm along its direction of application.*

In the S.I. system, the unit of work is the ***joule*** which is *the work done when a force of one newton acts through a distance of one metre in the direction of its application.* The symbol of joule is J.

Since one newton=10^5 dyne and a metre = 10^2 cm, **1 joule=10^7** ergs. The erg is so small a unit that work is often expressed in joules even when C.G.S. System is used.

Gravitational units. In practice, the work is generally measured in gravitational units. In the C.G.S. system, the gravitational unit is called **gram-centimetre (gm cm).** *It is the amount of work done by a force of 1 gm wt, in moving a body through a distance of 1 cm along its direction of application.*

In the S.I. system, the gravitational unit is called **kilogram metre.** *It is the amount of work done when a force of 1 kg wt moves a body through a distance of 1 m along its direction of application.*

Since gravitational unit of force is g times the absolute unit of force, the gravitational unit of work must also be g times the absolute unit of work.

Thus 1 gm cm = 981 ergs
and 1 kg m = 9.8 joules

From the above discussion, we may write the following four equations which are very useful for solving numerical problems.

Work (erg) = Force (dyne) × Distance (cm)
Work (gm cm) = Force (gm wt) × Distance (cm)
Work (joule) = Force (N) × Distance (m)
Work (kg m) = Force (kg wt) × Distance (m)

System	Absolute units	Gravitational units
SI	JOULE (or newton-metre) 1J = 1N × 1 m	**kg-metre** 1 kg m = 1 kg wt × 1 m
C.G.S.	ERG 1 erg = 1 dyne × 1 cm	gm-cm 1 g cm = 1 gm wt × 1 cm

5.3 POWER

In Physics, the term *power means the rate of doing work or work done per unit time*. If a certain agent is able to complete W joules of work in t seconds, its power (P)

$= \frac{\text{work done}}{\text{time taken}} = \frac{W}{t}$ J/s. Thus the term *'power' adds the idea of time to the work done.*

Units of power. In the C.G.S. system, the absolute unit of power is 1 erg/s. But it is too small a unit for practical purposes. The practical unit of power in the C.G.S. system is called **watt.** *Power is said to be 1 watt if work is being done at the rate of 1 J/s.*

A bigger unit of power is **kilo-watt (kw)** which is the rate of doing 1000 joules of work in one second. Thus,

$$\boxed{\text{1 kilo-watt} = \text{1000 watt}}$$

The power of the electric motors, dynamos, fans and other electric appliances is generally expressed in watt.

One *megawatt (MW)* = 10^6 watts.

In S.I. System, the unit of power is the *watt.*

Another practical unit of power is called **Horse-Power.** This unit was introduced by James Watt, the inventor of the steam engine. In his days, horses were used to operate the machinery in coal mines and also to drive other types of machines in his country. James Watt wanted to replace these horses by his engines.

$$\boxed{\text{1 H.P.} = \text{746 watts}}$$

5.4 ENERGY

Capacity of a body to do work is called **energy.** It is measured in the same units as work, *i.e.*, erg and joule etc. It is also measured in **kilo-watt hour (KWH).**

1 kilowatt hour = 36×10^5 joules

It is of two kinds. *When the energy is due to the motion of a body, it is called* **Kinetic Energy**. *When energy of a body is due to the relative position of its parts or the body as a whole, although the body is at rest, it is known as* **potential energy**.

Kinetic energy and potential energy taken together are called **mechanical energy**.

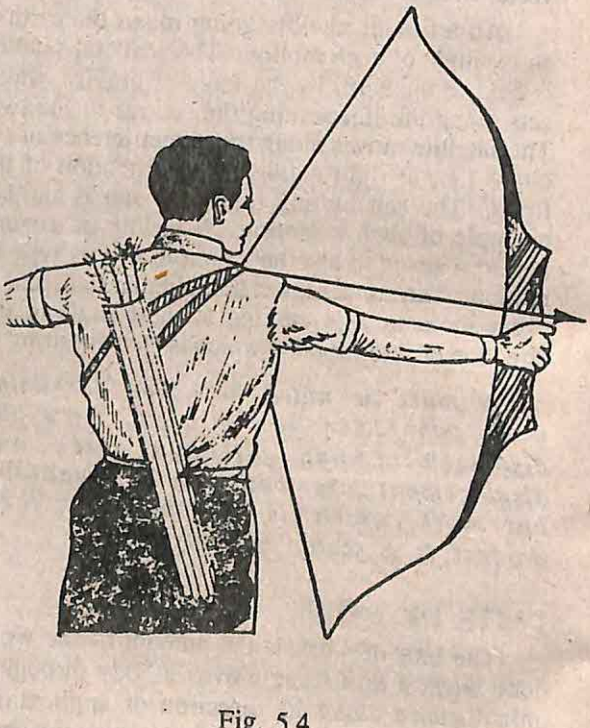


Fig. 5.4

Energy obtained by a water-wheel is derived from water which is falling from a height. Moving air drives round the sails of a wind-mill. The moving hammer drives in a nail. These are all examples of energy.

Water at the top of a *water fall* has potential energy. As it falls, it gradually loses this potential energy, but acquires kinetic energy at the same rate. At the bottom of the *fall,* the potential energy has completely changed into kinetic energy. A watch spring when wound up has potential energy and this changes to kinetic energy of the balance wheel which otherwise comes to rest.

A bent bow Fig. 5.4 has potential energy due to the change of position of the particles of the bow and the forces between them. As it unbends, it loses this potential energy and the arrow gains kinetic energy.

In a toy pistol when the compressed spring is released by the trigger, the P.E. of the compressed string is used to throw out the cork. Similarly the P.E. of the stretched rubber band in a catapult is used to throw a stone.

5.5 INTERCHANGE OF KINETIC AND POTENTIAL ENERGY

Interchanges of kinetic and potential energy are common in nature and industry and a few examples may briefly be stated here :

(*a*) **Change from Kinetic to Potential Energy**

- (*i*) When the motion of a train is checked by a spring buffer, kinetic energy is changed into potential energy.
- (*ii*) When the bob of a vibrating pendulum moves from the mean position to its extreme position, the K.E. is changed into P.E.

(*b*) **Change from Potential to Kinetic Energy**

- (*i*) Water in a dam has potential energy. When allowed to escape to a lower level, it loses part of its potential energy ; either gains kinetic energy itself or, if it acts on a water-wheel or turbine, imparts kinetic energy to the latter.
- (*ii*) When the bob of a vibrating pendulum moves from the extreme position to the mean position, the P.E. is changed into K.E.

(*c*) **Periodic Interchanges.** In the case of a vibrating body such as a pendulum, a tuning fork or a violin string, energy continually changes from the kinetic to the potential form and *vice versa.*

(*d*) **Complex Changes.** There are some changes of energy which are very complex but they do illustrate that energy can neither be created nor destroyed and man can only transform it from one kind into another. For example, a labourer carrying bricks up a ladder is not *creating* potential energy, but is only *converting* some of his internal store of energy into another form. After a certain interval, rest and food will be necessary in order that his internal store of energy may be replenished. No matter what may be the form of food, it is derived ultimately from vegetation, and vegetation depends for its growth upon the light and heat of the sun. Hence the store of energy in the sun is responsible primarily for all the *energy* or *life* on the earth.

5.6 MEASUREMENT OF POTENTIAL ENERGY

The simplest case of a body having P.E. is that of a body raised through a height h above the ground level (Fig. 5.5). Other cases having such type of energy are too complex to be discussed here. If m be the mass of a body raised through a vertical distance h, an amount of work *mgh* is required to be done on the body against the force of gravity. This work is stored up in the body as potential energy. ***Hence the expression mgh is the measure of potential energy (W) of the body of mass m when raised through a height h above the surface of the earth.*** It must be noted here that potential energy is a relative term which varies with the position of the level of reference. In the above mentioned case the level of reference is that of the surface of the earth. The absolute level taken generally in such cases is the average sea-level.

5.7 MEASUREMENT OF KINETIC ENERGY

The kinetic energy (T) of a moving body is measured by the expression,

$$\text{K.E. (T)} = \frac{1}{2} m \, V^2$$

where, m = mass of the body,
V = velocity of the body.

This expression is deduced as follows :

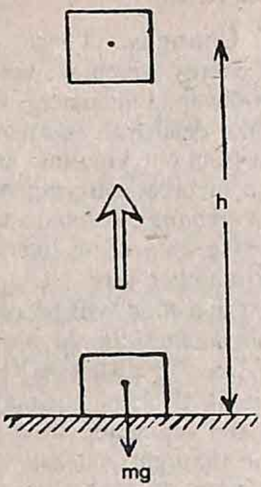


Fig. 5.5

Kinetic energy is due to motion. To set an object in motion work must be done on it. For a moving object to stop, it must exert a force on something else (which also pushes back) and it does work on this other object. To find how the kinetic energy of an object depends on the various physical factors, the amount of work done on an object to stop it must be found.

Suppose a body of mass m is moving with a velocity v and is at A at a certain instant (Fig. 5.6).

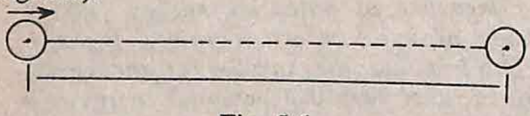


Fig. 5.6

A force F is applied on it from the opposite direction. Suppose the body comes to rest when it reaches B, such that the distance AB = S.

The work done by the force on the body is given by

Work = Force × Distance
= F.S.

This work has destroyed the motion and hence is equal to the kinetic energy of the body. We can say that the body also would have done the same amount of work if its motion had not been destroyed by the retarding force or the kinetic energy (T) of the body is also F.S.

Thus, K.E. = F.S.
Now for this journey the body has
initial velocity $= u = v$
final velocity $= 0$
distance moved $= S = S$
(*negative*) acceleration $= a = -\frac{F}{m}$
Applying the formula

$$v^2 - u^2 = 2aS$$

We have

$$0 - v^2 = 2aS$$

$$0 - v^2 = 2\left(\frac{-F}{m}\right)S$$

$$-v^2 = -2.\frac{F}{m}.S$$

$$v^2 = 2.\ \frac{F}{m}.S$$

$$\frac{1}{2}mv^2 = F.S.$$

$$= K.E.$$

Thus the kinetic energy of a moving body is equal to half the product of its mass and the square of its velocity.

It is also clear from the above discussion that work done = W = F.S.

Since $F = ma$
and distance covered $(S) = \frac{1}{2a}(V^2 - u^2)$

$$\therefore \quad W = ma.\frac{1}{2a}(v^2 - u^2)$$

$$= \frac{1}{2}mv^2 - \frac{1}{2}mu^2$$

= Final K.E. – Initial K.E.
= Change in K.E.

Thus, when work is done on a body by the force, its kinetic energy changes.

5.8 LAW OF CONSERVATION OF ENERGY

It was noted earlier that in the case of a vibrating body, like a pendulum, the energy goes no changing from kinetic to potential and back to kinetic again. Such phenomena lead us to the conclusion that energy like matter is indestructible. A given quantity of kinetic energy may be converted into an equivalent quantity of another form of energy. A given quantity of kinetic energy can be converted into an equivalent quantity of heat or mechanical work or chemical action.

The Law of Conservation of Energy based upon the above-mentioned changes can be stated as follows :

(a) **Energy can neither be created nor destroyed.**
(b) **The total amount of energy in the universe is constant.**
(*c*) **When a certain amount of energy in one form is expanded, its exact equivalent amount reappears in one or more of the other forms.**

In all the interchanges in the form of energy, sooner or later, it assumes the form of heat, which in due course becomes distributed throughout space. It probably becomes unavailable, but is still there, though scattered.

The principle of conservation of energy is best illustrated by (*i*) a body falling freely under gravity and (*ii*) a vibrating pendulum.

(*i*) **Body Falling freely under Gravity :**

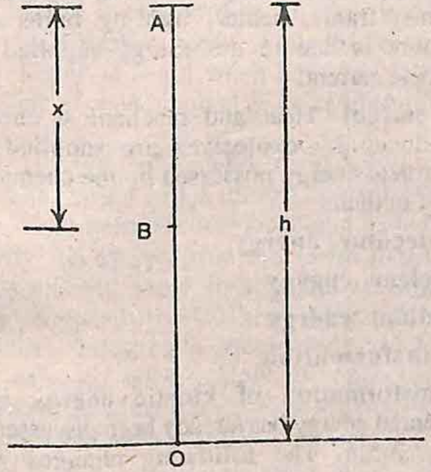


Fig. 5.7

Let a body of mass m be raised from the ground level O to A at a height h [Fig. 5.7]. The work done on the body to raise it against the force of gravity is mgh. This work is stored in the body. Let the body at A be at rest. At A,

$$\text{K.E.} = 0$$
$$\text{P.E.} = mgh$$
$$\text{K.E.} + \text{P.E.} = mgh \qquad ...(1)$$

Let the body now fall through a distance x and come to B.

To obtain the velocity at B, we have the data

$$u = 0$$
$$v = ?$$
$$a = g$$
$$s = x$$
$$\therefore \quad v^2 - u^2 = 2as$$
$$\therefore \quad v^2 - 0 = 2gx$$
$$\text{or} \quad v^2 = 2gx$$

Hence, at B,

$$\text{K.E.} = \frac{1}{2} mv^2$$
$$= \frac{1}{2} m.\, 2gx = mgx$$
$$\text{P.E.} = mg\,(h - x)$$
$$\therefore \quad \text{K.E.} + \text{P.E.} = mgx + mg\,(h - x)$$
$$= mgh$$

On reaching O, the velocity v of the body is given by

$$\mathrm{v}^2 = 2gh \qquad ....(2)$$

Hence, at O,

$$\text{K.E.} = \frac{1}{2} m.\, \mathrm{V}^2$$
$$= \frac{1}{2} m.\, 2gh = mgh$$
$$\text{P.E.} = 0$$
$$\text{K.E.} + \text{P.E.} = mgh \qquad ....(3)$$

The equations (1), (2) and (3) show that the total energy of a body falling freely under gravity remains constant and is always equal to mgh which is dependent of x or the position of the body during its fall.

On striking the ground, the body finally comes to rest. The K.E. possessed by the body is thus lost, being converted into other forms *e.g.*, heat and sound.

(*ii*) **Vibrating Pendulum.** The bob of a pendulum is raised up through a distance as it moves to the right extreme position C. Its P.E. has thus been increased. Here the bob is at rest for a moment. Therefore, it has no K.E. As it comes to the mean position A, its P.E. [Fig. 5.8] has changed into K.E. The sum total of energy would, however, be constant. The energy change takes place in the reversed direction as the bob moves to the left extreme position B. K.E. is again changed into P.E. In-between the extreme position and the mean position, the energy is partially potential and partially kinetic in such a way that the sum is constant.

5.9 DISSIPATION OF ENERGY

In the case of a vibrating pendulum energy changes from kinetic to potential and back again periodically. But ultimately the bob comes to rest owing to the resistance by air etc. The question arises what happens to the energy possessed by the bob. It has disappeared as heat and is said to have been wasted as the heat energy so produced cannot be used again for any useful purpose. Similarly when a moving bullet strikes against a target, the energy of the bullet is converted into heat energy and sound energy which cannot be utilized for any useful purpose. Thus energy of all form is ultimately converted into heat although it may pass through several states. *The energy which disappears as heat and cannot be used again for any useful purpose is said to have been dissipated.*

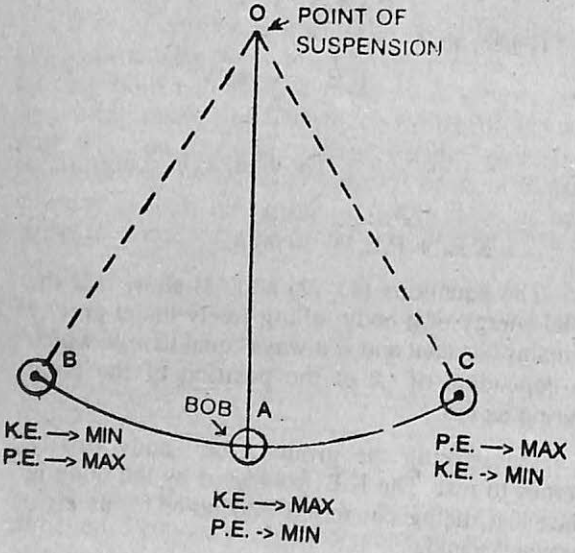


Fig. 5.8

In converting energy from one form into another, some of the energy disappears generally so that total energy in the new form is less than the original energy. This missing energy is converted into forms other than that desired, and the total energy in the various final forms is exactly equal tothe original energy and the principle of conservation of energy is never violated.

5.10 FORMS OF ENERGY AND TRANSFORMATION OF ENERGY

[A] Forms

In addition to the two forms of energy, kinetic and potential, there are several other forms of energy which are enumerated below :

(*a*) **Heat.** Energy supplied by the steam or oil engines is obtained from heat.

(*b*) **Light.** In photography light energy supplies the necessary chemical energy for the process.

(*c*) **Sound** is definitely a form of energy as glass panes of doors and windows of buildings in the vicinity of a big explosion are known to be shattered to pieces on account of the effect of the sound.

(*d*) **Magnetic.** A piece of iron when attracted by a magnet moves towards it and motion is the result of magnetic energy.

(*e*) **Electricity :**

Static electricity. Motion of electrified bodies is the result of attraction or repulsion due to electric charges residing on the bodies.

Current electricity. Working of electric trains, trams, heater, lighting bulbs and motors is due to the energy supplied by electric current.

(*f*) **Chemical.** Heat and mechanical energy produced by explosives are supplied by chemical energy possessed by the chemicals used in them.

(*g*) **Molecular energy**

(*h*) **Nuclear energy**

(*i*) **Radiant energy**

[B] Transformation

(*a*) Transformation of kinetic energy into potential energy has already been discussed in Art. 2-5.8. The following changes will illustrate the principle of transformation of energy more fully.

(*b*) **Kinetic to Heat.** Heat is produced when a moving wheel of an engine is stopped by applying brakes.

(*c*) **Gravitational to Electrical.** Electrical energy is produced by water turbines.

(*d*) **Heat to Light.** A red hot ball emits light.

(*e*) **Light to Chemical.** The chemical action on the photographic plate is due to light energy.

(*f*) **Heat to Electricity.** Electric current is produced by heating one of the junctions of two dissimilar metals.

(*g*) **Heat to Kinetic.** A steam engine changes heat energy to kinetic energy.

(*h*) **Chemical to Heat.** When coal burns, heat is produced.

(*i*) **Chemical to Electrical.** In a voltaic cell, electric current is produced by a chemical action.

(*j*) **Electric to Chemical.** In electrolysis, the electrolyte is decomposed into its constituent parts.

(*k*) **Electrical to Heat and Light.** In an electric heater and electric bulb, electric current produces heat and light respectively.

(*l*) **Electrical to Mechanical.** In electric trams and fans, the electrical energy is changed into mechanical energy.

(*m*) **Mechanical to Electrical.** In a dynamo, electric current is produced by rotating the armature in a magnetic field.

(*n*) **Electrical to Sound.** In electric bells, sound is produced by an electric current. A loudspeaker converts electricity in sound. Sound is heard when lightning falls from a cloud on the ground or on another cloud.

5.11 ESCAPE VELOCITY*

The faster a ball is thrown upwards, the higher does it rise before it is stopped and pulled back by gravity. To escape from the earth into the outer space we will show shortly that an object must have a speed of 11.2 km/s called the *escape velocity*. Thus *escape velocity may be defined as the velocity with which an object must be projected in order that it may escape the earth's gravitational pull.*

Launch a projectile at any speed greater than 11.2 kms^{-1} and it will leave the earth, travelling slower and slower, but never stopping due to earth's gravity. Recall Newton's law of gravitation in Chapter 2-3 : the ever present force of earth gravity weakens and is less effective with increasing distance. We can understand the magnitude of this escape velocity from an energy point of view. *The escape velocity is obtained from the fact that the potential energy gained by the body equals its loss of kinetic energy.*

We learnt in Chapter 2-3 that the force of gravity between the earth and an object of mass *m* is given by

$$F = \frac{GM\,m}{R^2} \quad \text{(Newton's law of gravitation)}$$

where F = Force of gravity between the earth and the object
G = Gravitational constant
M = Mass of the earth
m = Mass of the object
R = Radius of the earth.

The object has to have sufficient energy to do work against the earth's gravity.

$$\text{The work to be done} = F \times R$$

$$= \frac{GM\,m}{R^2} \times R = \frac{GMm}{R}$$

The kinetic energy of the object $= \frac{1}{2} m\vartheta^2$

where ϑ is the escape velocity of the object.

For the object to overcome the earth's pull,

$$\frac{1}{2} m\,\vartheta^2 > \frac{GMm}{R}$$

$$\text{or } \vartheta^2 > \frac{2GM}{R}$$

$$\text{or } \vartheta > \sqrt{\frac{2GM}{R}}$$

$$\text{or } \vartheta > \sqrt{2Rg}$$

because acceleration due to gravity $g = \frac{GM}{R^2}$

(See Chapter 2-3)

The least value for the escape velocity ϑ

$$\vartheta = \sqrt{2Rg} = \sqrt{\frac{2GM}{R}}$$

Since

$$g = 9.8 \text{ m/s}^2$$

$$R = 6.38 \times 10^6 \text{ m, we have}$$

$$\vartheta = \sqrt{2 \times 6.38 \times 10^6 \times 9.8 \text{ ms}^{-1}}$$

$$= \boxed{11.2 \text{ kms}^{-1}}$$

Any object with velocity greater than 11.2 kms^{-1} will escape into space.

---

* For knowledge only.

Notice that this escape velocity from the earth is the *same* for any object no matter what its mass is. It depends only on the mass and radius of the earth.

The escape speeds or, if direction is involved, the escape velocities of various bodies in the solar system are shown in Table 2-5.1.

Table 2-5.1
Escape speeds at the surface of bodies in the solar system

Astronomical body	*Escape speed* (kms^{-1})
Sun	620
Jupiter	61.0
Saturn	37.0
Neptune	25.4
Uranus	22.4
Earth	11.2
Venus	10.4
Mass	5.2
Mercury	4.3
Moon	2.4

It turns out that the escape speed of 11.2 kms^{-1} of the earth corresponds to a kinetic energy of 60 million joules for each kilogram, whatever the total mass involved. If we give a payload any more energy than 60 MJ per kilogram at the surface of the earth or, equivalently, any more speed than 11.2 kms^{-1}, `then, neglecting air resistance, the payload will escape from the earth never to return. As it continues outward, its P.E. increases and its K.E. decreases. Its speed becomes less and less, though it is never reduced to zero. The payload outruns the gravity of the earth. It escapes.

The first probe to escape the solar system, *Pioneer 10,* was launched from earth in 1972 with a speed of only 15 kms^{-1}. Pioneer 10 passed the orbit of Pluto in 1984. Unless it collides with another body, it will wander indefinitely through interstellar space.

SOLVED EXAMPLES

Example 1.

Calculate the work done in lifting a weight of 4 kg through a vertical height of 10 m. (Take $g = 9.8\ ms^{-2}$)

Solution :

The force (F) required to lift a mass (m) is equal to its own weight mg. Thus $F = mg$

Work done = Force × distance moved by force

$= m.g \times h$

$= 4 \times 9.8 \times 10$ newton metre

$= \boxed{\textbf{392 joules}}$

Example 2.

A man weighing 110 kg lifts a weight of 90 kg to the top of a building 30 m high in one minute. Find the work done and power. ($g = 9.8\ ms^2$).

Solution :

Here,

Total mass (m) = 110+90 = 200 kg

∴ Force acting vertically downwards

$= F = mg = 200 \times 9.8$ N

Distance = 30 m

time = t = 1 minute = 60 s

Now, work done = force × distance

$= 200 \times 9.8 \times 30 = 58800$ J

$$\text{And Power (P)} = \frac{\text{Work done}}{\text{Time}}$$

$$= \frac{58800}{60} = 980 \text{ watt} = \boxed{0.98 \text{ kilowatt?}}$$

Example 3.

What is the work done by a man in carrying a suitcase weighing 20 kg, over his head when he travels a distance of 10 m in the

(*i*) Vertical direction

(*ii*) Horizontal direction ?

($g = 9.8\ m/s^2$)

Solution :

Here mass (m) = 20 kg

∴ Force (F) = mg = $20 \times 9.8\ N$

Distance (S) = 10 m

(*i*) Work done in vertical direction = $F \times S$

$= 20 \times 9.8 \times 10 = \mathbf{1960\ J}$

(*ii*) Work done in horizontal direction =

Magnitude of the displacement vector × Projection of the force vector on the displacement vector

$= 10 \times 0$

$= 0$

since in this case, the projection of the force vector on the displacement vector is zero.

Example 4.

An elevator lifts a 2 kg mass through 20 m. How much potential energy is given to the mass ? ($g = 9.8\ m/s^2$)

Solution :

Here, mass (m) $= 2\ kg$

height (h) $= 20\ m$

Since Potential Energy ($P.E.$) $= mgh$

$\therefore \quad P.E. = 2 \times 9.8 \times 20 =$ **392 J**

Example 5.

Find the kinetic energy of body of mass 10 kg moving with velocity of 80 m/s.

Solution :

Here, mass (m) $= 10$ kg

velocity (v) $= 80\ ms^{-1}$

$\therefore$ $K.E.$ of the body $= \frac{1}{2}mv^2$

$$= \frac{1}{2} \times 10 \times (80)^2 = 32000\ J$$

Example 6.

What power in KW and $H.P.$ is required to lift 90 tonnes of coal per hour from a mine 200 m deep ? ($g = 9.8\ m/s^2$)

Solution :

Here, mass (m) $= 90$ tonnes $= 90000$ kg

Height (h) $= 200$ m

Time (t) $= 1$ h $= 3600$ s

Now, Force (F) $= mg$

$= 90000 \times 9.8\ N$

$\therefore$ Work done (W) in 1 h $= F \times h$

$$= mgh$$

$$= 90000 \times 9.8 \times 200 \text{ joules}$$

$$\therefore \text{Power } (P) = \frac{\text{Work done}}{\text{Time}} = \frac{W}{t}$$

$$= \frac{90000 \times 9.8 \times 200}{3600} \text{ watt}$$

$$= \mathbf{49000\ W = 49\ kW}$$

Since 1 $H.P.$ $= 746\ W$ $\therefore$ Power

$$\therefore \text{Power} = \frac{49000}{746} = 65.7 \text{ H.P.}$$

Example 7.

A man moves a trolley of machinery over a horizontal surface at a constant velocity by pulling along the handle with a constant force. If the handle

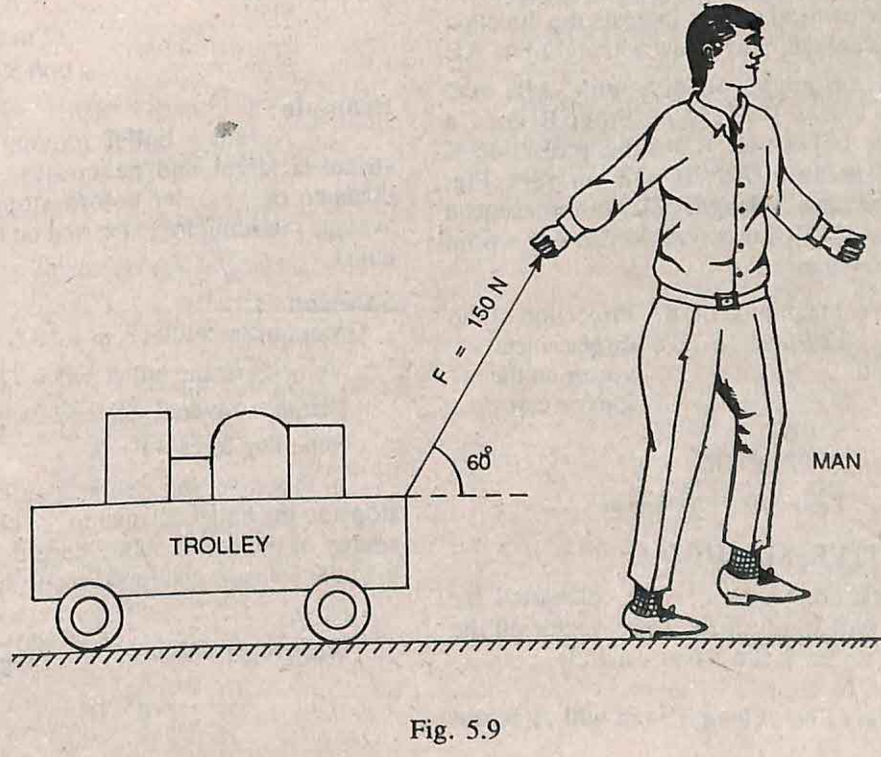
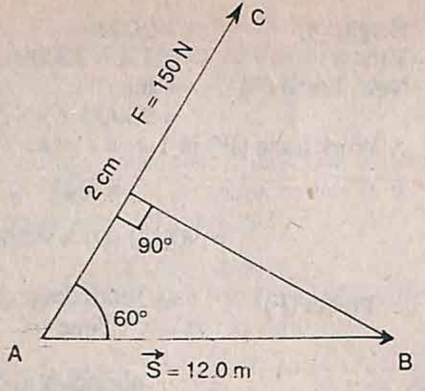


Fig. 5.9



(Scale 1 cm = displacement of 3 m)
Fig. 5.10

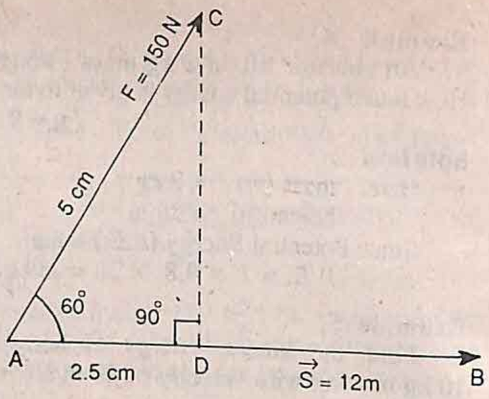


Fig. 5.11

of the trolley is inclined at 60° with the horizontal, how much work does the man do on the loaded trolley if he exerts a 150 N force and the trolley moves 12.0 m ?

Solution :

Given

$F = 150\ \text{N}$

To represent the displacement vector, let us choose a convenient scale. Let 1 cm represent a displacement of 3 m. Hence a displacement of 12.0 m is represented by a straight line of length 4 cm. Draw a straight line **AB** of length 4 cm [Fig. 5.10] and put an arrowhead at B to indicate the direction of the displacement. Now draw a straight line **AC** subtending an angle of 60° with **AB.** $\overrightarrow{\mathbf{AC}}$ represents a force F = 150 N. From B draw a perpendicular BD on AC. AD is the projection of AB on AC. Measure AD. It is 2 cm [See Fig. 5.10]. On our scale, a length of 2 cm represents a displacement of 2 × 3 m = 6 m. Hence AD = 6 m. Now, we know that

Work done = Magnitude of the force × Projection of the displacement vector on the force vector

$$\text{or } W = F \times AD$$
$$= 150\ \text{N} \times 6\ \text{m}$$
$$= \mathbf{900\ Nm} = \boxed{\mathbf{900\ J}}$$

ALTERNATIVE METHOD :

The work done can also be calculated by drawing the projection of the force vector on the displacement vector. Let us choose a scale

1 cm = 30 N

so that a straight line of length 5 cm will represent a force of 150 N [See Fig. 5.11].

AD is the projection of the force vector on the displacement vector $\overrightarrow{AB}$. Measure AD. It is 2.5 cm. On our scale, a length of 2.5 cm represents a force of 2.5 × 30 N = 75 N

Hence $\overrightarrow{AD} = 75\ \text{N}$

Work done = Magnitude of the displacement vector × Projection of the force vector on the displacement vector

$$\text{or } W = \vec{S} \times \overrightarrow{AD}$$
$$= 12\ \text{m} \times 75\ \text{N}$$
$$= 900\ \text{Nm} = \boxed{\mathbf{900\ J}}$$

Example 8.

A 18.0 g bullet moving at 775 ms^{-1} strikes a target and penetrates horizontally a distance of 12.2 cm before stopping. Find the average retarding force exerted on the bullet by the target.

Solution :

Mass of the bullet = m = 18.0 g = 0.0180 kg

Velocity of the bullet = ϑ = 775 m/s

Distance covered = S = 12.2 cm = 0.122 m

Retarding force = F = ?

In this case, the work done by the target in stopping the bullet is equal to the change in kinetic energy of the bullet. Also, since the final speed of the bullet is zero, the final kinetic energy is zero.

Now,

Work done = W = F.S = change in K.E.

$$= \frac{1}{2} m\vartheta^2 - 0$$

$$= \frac{1}{2} m \vartheta^2$$

$$\therefore F = \frac{1}{2} \frac{m \vartheta^2}{S}$$

$$= \frac{1}{2} \times \frac{0.0180 \times (775)^2}{(0.122)} \text{ N}$$

$$= \boxed{\mathbf{44300\ N}}$$

Example 9.

Determine (i) the initial kinetic energy, (ii) the final kinetic energy, (iii) the change in kinetic energy, and (iv) the average braking force if a 1250 kg car brakes uniformly from 108 km/h to 36.0 km/h in a distance of 125 m.

Solution :

Given,

Initial velocity = $u = 108 \text{ km/h} = \frac{108 \times 1000}{(60 \times 60)}$

$= 30.0 \text{ ms}^{-1}$

Final velocity $= \vartheta = 36.0 \text{ km/h} = 10.0 \text{ ms}^{-1}$

Distance $= S = 125 \text{ m}$

Mass of the car $= m = 1250 \text{ kg}$

Force $= F = ?$

(i) Initial kinetic energy $= E_1 = \frac{1}{2} mu^2$

$$= \frac{1}{2} (1250 \text{ kg}) (30.0 \text{ ms}^{-1})^2$$

$$= \boxed{\mathbf{563000\ J}}$$

(ii) Final kinetic energy $= E_2 = \frac{1}{2} m\vartheta^2$

$$= \frac{1}{2} (1250 \text{ kg}) (10.0 \text{ ms}^{-1})^2$$

$$= \boxed{\mathbf{62500\ J}}$$

(iii) Change in kinetic energy $= E_2 - E_1$

$$= (62500 - 563000) \text{ J}$$

$$= \boxed{\mathbf{-501000\ J}}$$

(iv) Work done (W) =F.S.=Changein K.E.

$$\therefore \text{Force} = F = \frac{\text{Change in K.E.}}{S}$$

$$= \frac{-501000 \text{ J}}{125 \text{ m}}$$

$$= \boxed{\mathbf{-4000\ N}}$$

That is, 4000 N in the **opposite direction** to the motion.

Example 10.

A small 2 kg object falls from a height of 10 m into a box of sand. It comes to rest at a distance of 3 cm beneath the surface of the sand. How large was an average force exerted upon it by the sand ?

[Take $g = 9.8 \text{ ms}^{-2}$]

Solution :

Given,

$m = 2 \text{ kg}; h = 10 \text{ m}; \quad g = 9.8 \text{ ms}^{-2}$

$S = 3 \text{ cm} = 0.030 \text{ m}; \quad F = ?$

The potential energy is all changed to *K.E.* This in turn is all turned into friction work as the ball penetrates the sand. Therefore,

P.E. = friction work

or mgh = F.S.

or $2 \times 9.8 \times 10 = F \times 0.030$

$\therefore$ $F = \boxed{\mathbf{65\ N}}$

Example 11.

A man drops a 10 kg rock from the top of a 5 m ladder. What is its K.E. when it reaches the ground ? What is its speed just before it hits the ground ? ($g = 9.8 \text{ m/s}^2$)

Solution :

Given,

Mass of the rock $= m = 10 \text{ kg}$

Height of the ladder $= h = 5 \text{ m}$

K.E. = ?

Speed of the rock when it hits the ground$= \vartheta = ?$

According to law of conservation of energy,

K.E. of the rock = P.E. of the rock.

$= mgh = 10 \times 9.8 \times 5 \text{J}$

$= \boxed{\mathbf{490\ J}}$

Since, K.E. of the rock $= \frac{1}{2} m\vartheta^2$

$$\therefore \frac{1}{2} m\vartheta^2 = 490$$

$$\vartheta^2 = \frac{490 \times 2}{m} = \frac{490 \times 2}{10}$$

$$= 98$$

$$\therefore \vartheta = \sqrt{98} \text{ m/s}$$

$$= 7\sqrt{2} \text{ ms}^{-1}$$

$$= \boxed{\mathbf{9.89\ ms^{-1}}}$$

SUMMARY

1. Work is done on an object only if a force acts on the object and the point of application of the force moves along the direction of the force. In other words work is done whenever the application of force produces a change. The change may be in the position of the object, in its velocity, in its shape, in its chemical composition, in its temperature or even its colour.

   No work is done if any of the above conditions is not satisfied.

   Work is a *scalar* quantity.

2. Work done = Force × distance moved *along the direction of the force.*
   = Force × displacement *in the direction of the force.*

   If the force and displacement are *inclined* to each other,

   Work done = Magnitude of force × Projection of displacement vector on force vector

   = Magnitude of displacement × Projection of force vector on displacement vector.

   No work is done if force and the displacement are *at right angles* to each other.

3. The SI unit of work is *newton - metre* (Nm) or *joule* (J).

   One joule of work is said to be done when a force of one newton acting on a body moves it through a distance of one metre in the direction of the force.

4. An object having capability to do work is said to possess *energy*. It is measured in the *same* units as work.

5. The energy possessed by an object by virtue of its motion is called *kinetic energy.*

   $$K.E. = \frac{1}{2}mv^2$$

   $$\text{Work done (W)} = F.S. = \text{Change in K.E.}$$

   $$\text{or } W = F.S. = \frac{1}{2}m\vartheta^2 - \frac{1}{2}mu^2$$

   The energy possessed by an object due to its position or change of shape is called *potential energy.*

   $P.E. = mgh.$

   Both *K.E.* and *P.E.* taken together are called *mechanical energy.*

6. The work done per unit time or the rate of doing work is defined as *power (P).*

   $$P = \frac{\text{Work done}}{\text{Time taken}} = \frac{W}{t} = \frac{F \times S}{t} = F \times v \text{ where } \frac{S}{t} = \text{speed (v)}.$$

   Power is expressed in *joule/second* or *watt (W).*

   The capacity of machines to do work is expressed in terms of *watt* or *kilowatt (kW)* or *megawatt (MW).*

7. Change of energy from one form to another is called *transformation of energy.*

8. According to *law of conservation of energy,* **"energy can neither be created nor destroyed but can be transformed from one form to another."**

   Total energy of the system remains *conserved* in all natural processes.

9. The energy which appears as heat and cannot be used again for any useful purpose is said to have been *dissipated.*

10. The *escape velocity* is the velocity with which a body must be projected in order that it may escape the earth's gravitational pull.

    For earth the escape velocity is 11.2 kms^{-1}.

    $$J = \sqrt{2Rg} = \sqrt{\frac{2MG}{R}}$$

    where ϑ = velocity of escape
    R = Radius of earth (or any planet)
    g = Acceleration due to gravity
    M = Mass of earth (or any planet)
    G = Gravitational constant.

QUESTIONS

A. Objective Type Questions

1. The speed of an object is doubled. As a result its kinetic energy is

   (*a*) doubled (*b*) quadrupled (*c*) halved (*d*) quartered

2. Ashish weights 40 kg. He exerts a horizontal force of 20 N in pushing an object a horizontal distance of 3 m at constant speed. The work done by Ashish, in joules, is

   (*a*) 800 (*b*) 60 (*c*) 120 (*d*) zero

3. A 40 newton object is released from a height of 10 m. Just before it hits the ground, its kinetic energy, in joules, is

   (*a*) 400 (*b*) 3920 (*c*) 12800 (*d*) zero

4. In question (3), the kinetic energy of the object at a height of 8 m, in joules, is

   (*a*) 320 (*b*) 80 (*c*) 392 (*d*) 790

5. As an object falls towards the ground, its potential energy

   (*a*) increases (*b*) decreases (*c*) remains the same

6. A box which weighs 10 N is dragged across a level floor by a horizontal force of 3 N for a distance of 5 m. The work done, in joules, is

   (*a*) 15 (*b*) 30 (*c*) 50 (*d*) 500

7. As the time required to raise a given weight 6 m decreases, the power needed

   (*a*) increases (*b*) decreases (*c*) remains the same

8. If air resistance is negligible, as an object falls towards the ground, the sum of its potential and kinetic energies

   (*a*) increases (*b*) decreases (*c*) remains the same

9. Ram carries his brother Arun on his shoulders along the level ground. If Arun weighs 30 kg and he is carried for a distance of 10 m, the work done on him by Ram, in joules, is ....

10. A 5 kg mass is raised 8 m above the ground. Its change in potential energy with respect to the ground, in joules, is

    (*a*) 40 (*b*) 80 (*c*) 200 (*d*) 390

11. The speed of an object having a mass of 5 kg and a kinetic energy of 360 *J*, in ms^{-1}, is

    (*a*) 12 (*b*) 38 (*c*) 72 (*d*) 144

12. A 30 N object rests on a table 1.2 m high. The work done by the table in supporting the object, in joules, is

    (*a*) zero (*b*) 30 (*c*) 36 (*d*) 350

13. A man exerts a force of 500 *N* on a car that does not move. If the car weighs 1500 kg, the amount of work done by the man is ....

14. Almost the whole of our available energy comes from ......

15. The unit in which energy is measured is the

    (*a*) Watt (*b*) Joule per coulomb (*c*) Coulomb (*d*) Joule (*e*) volt-second

16. Power is a measure of the

    (*a*) rate of change of energy (*b*) rate of change of momentum (*c*) Force which produces motion

    (*d*) Change of energy (*e*) Total work done

17. 1 *H.P.* = ...*W*

18. 1 *W* = ... *J/s*= ....ergs/second

19. Two objects of masses 1.0×10^{-3} kg and 4.0×10^{-3} kg have *equal momentum*. What is the ratio of their kinetic energies ?

    (*i*) 4 : 1 (*ii*) 2 : 1 (*iii*) 16 : 1 (*iv*) $\sqrt{2}:1$

20. An iron sphere of mass 30 kg has the same diameter as an aluminium sphere whose mass is 10.5 kg.

The spheres are dropped simultaneously from a cliff. When they are 10 m from a ground, they have the same

(*a*) momentum (*b*) acceleration (*c*) potential energy (*d*) kinetic energy

21. In SI system the unit of potential energy is

(*i*) watt (*ii*) joule (*iii*) newton (*iv*) newton/metre^2.

B. Very Short Answer Type Questions

1. Define : Work.
2. What is the unit of work ? (*A.I.S.S. 1986*)
3. Define : Power. (*A.I.S.S. 1986*)
4. Give the unit of power.
5. Define : Energy.
6. Give the unit of energy.
7. Define joule.
8. Define watt.
9. Define kinetic energy.
10. Give the unit of *K.E.*
11. Define potential energy.
12. Give the unit of *P.E.*
13. List three formulas that can be used to calculate power.
14. Write an expression for the potential energy of an object which it gains as a result of being lifted.
15. How do the mass and speed of an object affect its kinetic energy ?
16. What happens to the energy which is used to move an object against friction ?
17. Give a labelled diagram to illustrate the conservation of energy by a swinging pendulum.
18. Does a man standing at rest on a moving box car possess kinetic energy ?
19. Is kinetic energy a vector or a scalar quantity ?
20. A ball of mass m is held at a height h_1 above the table. The table top is a height h_2 above the floor. One person says that the ball has a potential energy mgh_1, while another person says that its potential energy is $mg\ (h_1+h_2)$. Who is correct ?
21. Define erg.
22. Define horse power.
23. Is potential energy a vector or a scalar quantity ?
24. Is work a vector or a scalar quantity ? (*A.I.S.S. 1986*)
25. What is the K.E. of a ball of mass 1 kg moving with a velocity of 1ms^{-1} ?
26. What is the P.E. of an object of mass 1 kg held at a height of 1 m above the surface of the earth ?

C. Short Answer Type and Essay Type Questions

1. Does a block of wood released at the bottom of a lake possess potential energy ? Explain.
2. As a rocket re-enters the atmosphere, its nose cone becomes very hot. Where did this heat energy come from ?
3. A ball hangs as a pendulum from a piece of string. If the pendulum is set swinging, it stops each time it comes to the end of its swing. Discuss the variation of *K.E.* and *P.E.* in this system. Does the tension in the string do work ? Why does the pendulum eventually stop ?
4. What becomes of the original kinetic energy :

   (*i*) When a bullet embeds itself in a bag of sand ?

   (*ii*) When a boy claps his hands together ?
   and

(*iii*) When a hammer hits a nail ?

5. Is anything doing work to keep the earth rotating about the sun ? Explain.

6. Various hydroelectric plants use water-driven turbines to generate electrical energy. Trace this energy back as far as you can toward its source.

7. (*a*) Explain the terms : Work, Power and Energy and give the units for measuring these quantities.

(*b*) How are joule, erg and watt related to each other ? Is work a vector quantity ?

8. What do you mean by physicists' definition of work ? How is it measured ? Show that a person walking along a horizontal road with some load on his head is *not* doing any work.

9. Distinguish between *K.E.* and *P.E.* Give *three* examples of each. How are *K.E.* and *P.E.* measured ?

10. Derive an expression for the kinetic energy of a body of mass m moving with a velocity v. By how much will the *K.E.* of a body increase if its speed is doubled ?

11. Derive an expression for the potential energy of a body of mass m when it is raised to a height h from the ground level. [*A. I. S. S. 1983*]

12. (*a*) State principle of conservation of energy.

(*b*) Show that the sum of kinetic energy and potential energy of a falling body is constant at all points.

13. (*a*) What is transformation of energy ? Explain with the help of four examples.

(*b*) A ball rolling on the ground comes to rest. Where does its energy go ?

14. Mention the various sources of energy. Justify the statement that sun is the ultimate source of all energies.

15. What is negative work ? Give examples of positive and negative work.

16. Will there be any work done on a body moving with uniform speed in a circle ?

17. If energy is neither created nor destroyed, where does so much energy spent against friction in this life go ?

18. Give one example in each case, for the following transformation of energies :

(*i*) Chemical energy to electrical energy.
(*ii*) Electrical energy to mechanical energy.
(*iii*) Kinetic energy to gravitational potential energy.
(*iv*) Potential strain energy to gravitational potential energy.
(*v*) Electrical energy to light energy.
(*vi*) Electrical energy to sound energy.
(*vii*) Mechanical energy to heat energy.

19. Following is a list of some of the different forms of energy. Give *an example* in each case :

(*i*) Gravitational *P.E.* (*ii*) Kinetic energy (*iii*) Strain *P.E.* (*iv*) Heat energy (*v*) Chemical energy (*vi*) Electrical energy (*vii*) Molecular energy (*viii*) Radiation energy (*ix*) Nuclear energy (*x*) Mechanical energy.

20. Following are some examples of different forms of energy. Mention the *form* of energy in each case :

(*i*) A boulder on top of a cliff.
(*ii*) A bullet travelling through the air.
(*iii*) A stretched spring.
(*iv*) The fast moving molecules of a hot gas.
(*v*) Cold hydrochloric acid and sodium hydroxide solutions reacting to give a *warm* salt solution.
(*vi*) Electricity through a lamp providing heat and light.
(*vii*) Steam condensing to injure your hand.
(*viii*) Light coming from the sun.
(*ix*) Energy stored in the nucleus of an atom *i.e.*, the atomic bomb.

21. A labourer carrying bricks on his head on a level road from one place to another is doing no work ? Why ?

22. An iron ball and a wooden ball have the same momentum (*i.e.*, mass × velocity). Which has the greater *K.E.* ?

23. Here are some examples of force being used :
    (*a*) a tightened vice holding a glued joint together.
    (*b*) a motor engine dragging a load along a rough surface.
    (*c*) a wooden support shoring up a wall.
    (*d*) a donkey towing a cart along a road.

    Put the above list into two categories ; one where the forces involved are stationary, and the other where the forces involved are moving.

24. To lift a load a person must draw on his supply of food (*i.e.*, chemical) energy. In such a case what happens to the energy, does it get used up ?

25. Remembering that something which has energy can do a useful job, what test could be applied to see if there is energy stored in a raised load ?

26. Describe the *principle of energy transfers* involved in the following examples :
    (*i*) A waterfall is used to turn a paddle wheel. The paddle wheel works a dynamo which in turn lights a lamp.
    (*ii*) A battery drives on electric motor which works a pump to raise water from a well.
    (*iii*) A piece of sodium metal is dropped into cold water. It reacts violently to produce a warm solution of sodium hydroxide.
    (*iv*) A stretched spring contracts, raising a load from the ground.

27. Give an *example* in each of the following energy transfers :
    (*a*) Potential strain energy to gravitational *P.E.*
    (*b*) Chemical energy of the reagents to chemical energy of the reactants plus heat, light and sound energy.
    (*c*) Chemical energy to electrical energy to mechanical energy to gravitational *P.E.*

28. A pendulum is set up so that the thread will swing against a pin [Fig. 5.12].
    (*a*) If the pendulum bob is released from position *A*, what will be the energy changes as the bob moves to a new point of rest ?
    (*b*) If no energy is lost as heat through friction, where will the new point of rest be : at *B*, *C*, *D* or *E* ?

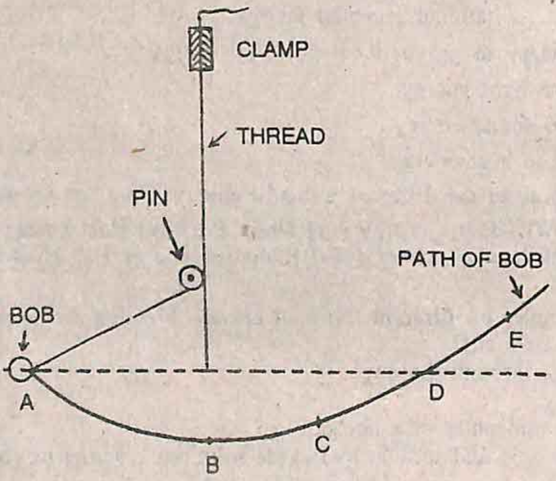


Fig. 5.12

29. A falling body weighing *m* kg has a velocity *v* m/s when it is '*h*' metres above the ground. Write down expressions for
    (*a*) its *P.E.*

(*b*) its *K.E.*

State the units corresponding to these expressions.

30. Briefly explain if any work is done during the orbital motion of a satellite. [*A.I.S.S. 1986*]

31. Why do the brakes of a car heat up when it is braked ?

32. Define escape velocity. What should be the velocity of a rocket so that it can escape the earth's pull ?

33. Can you say if the following objects have energy ? If they do, identify whether the energy is kinetic, potential or a combination of the two :

(*i*) A ceiling fan which has been switched off.
(*ii*) A man climbing a hill.
(*iii*) A flying bird.
(*iv*) Water in the reservoir of a dam.
(*v*) A spring expanded beyond its normal shape.
(*vi*) A rubber band lying on a table.
(*vii*) A stretched rubber band lying on a ground.

PROBLEMS

1. Two bodies of equal mass are kept at heights 'h' and '$3h$' respectively. What will be the ratio of their potential energy ? [**Ans.** 3 : 1]

2. Two bodies of equal mass move with velocities V and $2V$ respectively. Find the ratio of their kinetic energy. [**Ans.** 4 : 1]

3. Calculate the work done by a force of 50 N acting through a vertical height of 20 metre. [**Ans.** 10^3 J]

4. The height of the Qutab Minar is 72 m. What work a man of 50 kg weight does when he climbs up the top ? [**Ans.** 3.58×10^4 J]

5. A bullet of mass 5 g is fired with a constant velocity of 100 m/s. What is its kinetic energy ? [**Ans.** 25 J]

6. A body of mass 5 kg is placed on a table which is 5 metres high. Calculate the potential energy of a body. [**Ans.** 245 J]

7. Calculate the work done by a man in carrying a mass of 15 kg on his head when he covers a distance of 50 m in the horizontal direction. [**Ans.** zero]

8. A car is going on a level road. Its driver applies brakes to slow down the car from 60 km/h to 40 km/h. The mass of the driver is 60 kg and that of the car is 1140 kg. Calculate the work done in overcoming the friction offered by the brakes and the road.

To what fraction does the kinetic energy of the system reduce ? $\left[\textbf{Ans.}\ 92592.6\ \text{J}\ ;\ \frac{5}{9}\right]$

9. A 100 g apple falls from a tree and lands in a pond of water 5 m below. Calculate its initial *P.E.* and maximum kinetic energy. [**Ans.** 4.9 J ; 4.9 J]

10. A body of mass 3000 kg moves with a velocity of 50 m/s. What will be the stopping force, if it is brought to rest at a distance of 400 m ? [**Ans.** 9375 N]

11. A bullet of mass 50 g travelling with a velocity of 600 ms^{-1} has its velocity reduced to 150 ms^{-1} in passing through a target. Calculate the amount of energy dissipated. [**Ans.** 8437.5 J]

12. A pump is required to lift 500 kg of water per minute from a well 10 m deep and eject it with a speed of 10 ms^{-1}.

(*a*) How much work is done in lifting water ?
(*b*) How much work is done in giving it *K.E.* ?
(*c*) What is the power of the engine in kilowatt ? What is its *H.P.* ?

[**Ans.** (*a*) 816.6 J, (*b*) 25000 J, (*c*) 25.82 kW; 34.6 *H.P.*]

13. A force of 20 N is applied to a railway truck at an angle of 30° to the rails, the truck can only move 5 m along rails. Find the work done. [**Ans.** 86.6 J]

14. What is the power developed by the engines of a jet aircraft which gives a thrust of 7.4×10^4 N at 900 km/h ? **[Ans.** 1.85×10^7 W]

15. Calculate the *K.E.* of a ball of mass 10 g and momentum 1000 g cm/s. **[Ans.** 5×10^{-3} J]

16. A ball of mass 200 g falls through a height of 2 *m*. What is its *K.E.* when it reaches the ground ? **[Ans.** 3.92 *J*]

17. How much work is done by a force of 10 *N* in moving an object through a distance of 1 *m* in the direction of the force ? **[Ans.** 10 *J*]

18. Find the product of mass and velocity of a body of mass 100 g having a kinetic energy of 20 *J*. **[Ans.** 2 kg ms^{-1}]

19. If a man lifts 4 *N* through 6 *m* in 3 seconds, what is his power ? **[Ans.** 8 *W*]

20. (a) A strong man can easily and quickly lift a 50 newton weight through $1\frac{1}{2}$ metres. A boy can lift the same load through the same distance, but not so easily or quickly. How much work does the man do ?

(b) The boy does the same amount of work as the man, although it takes him longer. The man is more powerful than the boy because he works faster. If the man takes one second to lift the load and the boy takes three seconds, what are their rates of work in joules per second ?
[Ans. (*a*) 75 *J*, (*b*) 75 *W*; 25 *W*]

21. An electron travelling at a speed of 10^8 cm/s is to be brought to rest in a distance of 20 cm. How large must be the retarding force on the electron ? Mass of the electron = 9.1×10^{-31} kg. **[Ans.** 2.3×10^{-18} N]

22. A 0.50 g bead slides along a wire, as shown in Fig. 5.13.

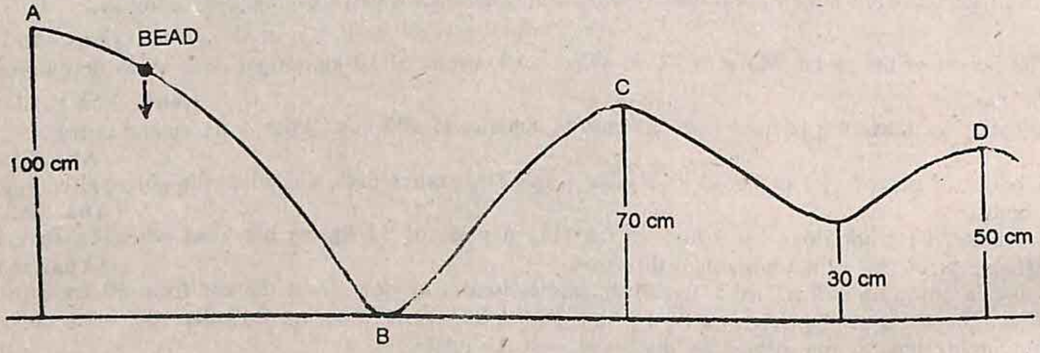


Fig. 5.13

If it starts from rest at point *A* and friction forces are negligible, how fast will it be going at points *B*, *C* and *D* ? (Take $g = 9.8$ ms^{-2}). **[Ans.** 4.4 ms^{-1}; 2.4 ms^{-1}; 3.1 ms^{-1}]

23. A ball at the end of a string acts as a pendulum. The pendulum is pulled aside so that the ball is at a distance *h* above its equilibrium position. If the ball is then released, show that its speed as it passes the equilibrium position (if one ignores friction) is

$v = \sqrt{2gh}$ where *g* is the acceleration due to gravity.

Show further that the ball dropped straight down through this distance has the same speed.

24. Calculate the power of a pump which can lift 250 kg of water to a water tank at a height 30 *m* in 10 seconds (Take $g = 10$ ms^{-2}). **[Ans.** 7.5 kW]

25. A man of mass 60 kg runs up a flight of 30 steps in 40 seconds. If each step is 20 cm high, calculate his power. **[Ans.** 90 *W*]

26. A block weighing 15 N slides down from the top of an incline plane making an angle of 30° with

the horizontal. Calculate the work done by the force of gravity in moving the block 5 *m* along the plane. Assume that the force of friction is zero.
[Ans. 37.5 *J*]

27. A block of 40 kg mass is pulled up a slope by applying a force acting parallel to the slope. If the slope makes an angle of 30° with the horizontal, calculate the work done in pulling the load up a distance of 6 m. What is the increase in potential energy of the block (Take $g = 10\ ms^{-2}$)
[Ans. 1200 *J* ; 1200 *J*]

28. A person of mass 50 kg climbs a tower of height 72 m. Calculate the work done. ($g = 9{\cdot}8\ ms^{-2}$).
[Ans. 35280 *J*]
[A.I.S.E.1983]

29. A body of mass 2 kg falls from rest. What will be its kinetic energy during the fall at the end of 2s ? Assume $g = 10\ m/s^2$.
[Ans. 400 *J*]
[A.I.S.E. 1981 (C)]

30. A body of mass 2 kg. is dropped from the top of a tower of height 50 m. If the acceleration due to gravity is $10\ m/s^2$, what will be its *K.E.* at the end of 2 s ?
[Ans. 400 *J*]
[A.I.S.E. 1982]

31. How much work is done by a force of 10 *N* in moving an object through a distance of 1 *m* in the direction of the force ?
[Ans. 10 *J*]
[A.I.S.E. 1982]

32. What is the K.E. of a body of mass 1 kg moving with a velocity of 2 ms^{-1} ?
[Ans. 2 *J*]
[A.I.S.E. 1982 (C)]

33. A horse and a dog are running with the same speed. If the weight of the horse is ten times that of the dog, what is the ratio of their kinetic energies ?
[Ans. 10 : 1]
[A.I.S.S. 1986]

34. A 10 g bullet is fired from a gun weighing 5 kg. If the speed of the bullet is 0.2 km/s, calculate the speed of recoil and the kinetic energy acquired by the gun.
[Ans. 0.4 m/s; 0.4 J]
[A.I.S.S. 1986]

35. A car weighing 1000 kg and travelling at 30 m/s stops at a distance of 50 m decelerating uniformly. What is the force exerted on it by the brakes ? What is the work done by the brakes ?
[Ans. 9000 *N*; 450000 *J*]

❑ ❑

CHAPTER – 6
WAVE MOTION

LEARNING OBJECTIVES :

At the completion of this Chapter, you should be able to grasp :

(*i*) the concept of a wave – a form of disturbance.

(*ii*) the concept of a pulse – disturbance for a short duration of time.

(*iii*) the meanings of mechanical waves and non-mechanical waves.

(*iv*) the idea that waves transport energy and not matter.

(*v*) the distinction between transverse waves and longitudinal waves.

(*vi*) the concept of a periodic wave and its characteristics.

(*vii*) the meanings of : amplitude, time- period, frequency, velocity and wavelength as related to a wave motion.

(*viii*) the relation between velocity of a wave, frequency and wavelength.

6.1. INTRODUCTION

In earlier chapters we studied the different types of motion a body can perform such as motion with uniform velocity and accelerated motion in a straight line, circular motion with uniform speed and a projectile motion. We then learnt to relate the acceleration of the body to the force applied. We also derived the distance travelled by such a body in a given period of time. We next studied the periodic motion of a body acted upon by a restoring force. We saw how the motion of such a body repeats itself after a fixed interval of time called its *period.* So far we restricted ourselves to the motion of an *isolated body* but we know that bodies rarely exist in isolation, *e.g.*, a liquid (water) consists of a large number of molecules closely packed with strong attractive forces between them. Similarly a solid (iron string) consists of a large number of particles very closely packed with strong attractive forces between them. Again, a gas (air) consists of molecules which are bound together by intermolecular forces.

If we move one particle of a solid or a liquid or a gas, the neighbouring particles (or molecules) get affected. In this Chapter we shall study the motion of a collection of particles or bodies – *Wave Motion*.

6.2. MOTION OF A COLLECTION OF BODIES (*WAVE MOTION*)

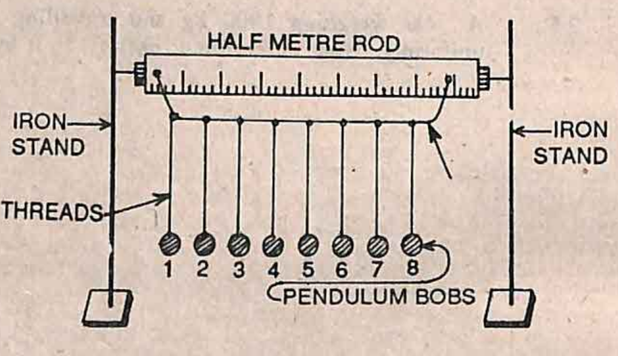


Fig. 6.1

Let us make a small set-up. Take a half metre rod and fix it horizontally between two clamp stands as shown in Fig. 6.1. Take a string about 60 cm long and tie its ends to the ends of the metre rod and fix it horizontally between two clamp stands as shown in Fig. 6.1. Now suspend eight *identical* pendulum bobs at the *same distance* from each other by tying firm knots. See that the bobs are at the *same height* from the ground.

Now hold bob 1 at the extreme left between your thumb and the first finger and pull it towards yourself by about 3 cm, *perpendicular* to the plane of the paper, which is the plane in which the threads of the pendulums lie, and release it. It starts oscillating in the plane of the strings of the pendulums. Take care that bob 1 does not collide with its neighbouring bob 2. You will notice that after some time the second bob starts oscillating, then the third, the fourth and so on until the last bob 8 starts oscillating.

Remember you had only disturbed the first bob from its mean (or equilibrium) position. Yet this disturbance *travelled* along until the last bob 8 felt this disturbance and started oscillating too. The oscillations of the first bob were able to cause oscillations in a bob far away from it without actually touching it. How does it happen ? If you notice, you would find that the bobs are coupled (or connected together) by means of the horizontal string to which their threads are tied. The *disturbance* created at bob 1 is communicated to bob 2 via this string. Bob 2 hands over its disturbance to bob 3 and so on until the last bob 8 receives the disturbance and begins to oscillate. Hence the disturbance is handed over from one bob to the next and so on.

If such a disturbance is created in a medium consisting of a very large number of particles very close together, this disturbance will travel from one particle to the next in exactly the same manner as it travelled from bob 1 to other bobs in the above mentioned experiment. *Such a disturbance which travels in a medium is called a wave motion* (or *a wave*).

***Wave motion** may, therefore, be defined as a form of disturbance which travels through an elastic material medium and is due to the repeated and periodic motion of the particles of the medium about their mean position, the motion being handed over from particle to particle.*

Examples of wave motion : Some of the examples of wave motion are given below :

1. Ripples in Water or Water Wave :

If anyone is asked to produce an everyday example of wave motion, almost the only ones that come to mind are *ripples* (or waves) *running over the surface of water* or the large-scale effects of *waves at sea* (Fig. 6.2).

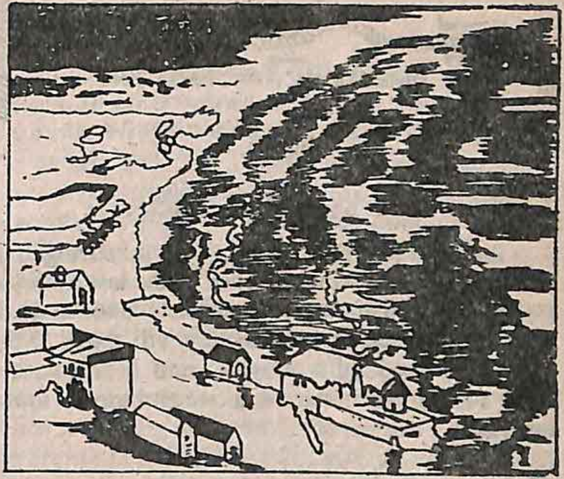


Fig. 6.2

Throw a piece of stone into a quiet tank of water. Circular ripples are formed and travel outwards from the point where the stone struck the surface of water. Let us see the mechanism by which these ripples have been formed. As soon as the stone strikes the surface of water, a depression is caused. Due to elasticity, water tries to recover its original level and in doing so fills up the depression. Owing to inertia of motion and hence kinetic energy of its particles, the water overshoots its mean position. This results in the formation of an elevation which is again followed by a depression and so on. Due to cohesion (*i.e.,* force of attraction between molecules of water), the neighbouring particles are also affected though a little later. Thus a wave train of elevations followed by depressions is formed. A piece of cork thrown on the surface of water will simply toss up and down when the ripples (or waves) reach it. It would, therefore, be clear to a careful observer that it is the disturbance which eventually reaches some distant part of the water tank and produces physical effects there, even though there is no actual transfer of water from the point of impact of the stone to the distant point.

2. A Wave on a String :

Another easy way to produce wave motion is to tie one end of a long rope to a window bar or a hook on the wall. If the free end of the rope is moved up and down, the disturbance will be seen to travel along the rope (Fig. 6.3).

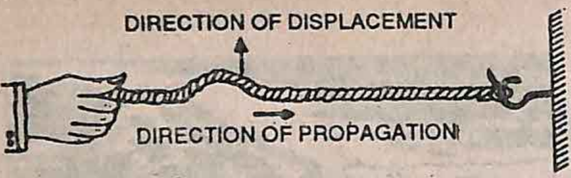


Fig. 6.3

3. Wave in a System of Trolleys :

Imagine a system of trolleys linked together by springs. The spring attached to the last trolley P is pulled (Fig. 6.4) and then released immediately. It will be observed that the trolley will move to the right, followed by trolleys R and S and so on. Thus a disturbance started at one end travels to the other end.

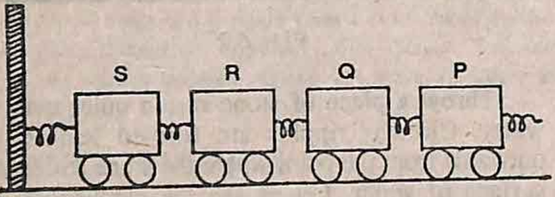


Fig. 6.4

4. Sound Wave :

When we speak, it is the oscillations of our "vocal cord" inside the throat that produce sound waves (Fig. 6.11). We disturb air molecules close to our mouth. These in turn disturb the ones nearby. This disturbance *travels*, oscillating the air molecules along its path until those molecules which are close to the listener's ears start oscillating too. These oscillations vibrate the ear drum which then sends the message to the brain through nerve connections.

Sound is produced by making things oscillate in a medium (air). When one strikes a drum, one can hear the sound, but one may not be able to see the oscillations of the membrane. Similarly when one plays on a *tabla*, one can hear sound. One may be able to observe the oscillations of the membrane of the *tabla* by placing a few small pieces of cork on it which will be found jumping up and down.

Let us see, from the above-mentioned examples, what common features of a wave motion are : A *disturbance* started at one place *progressively* moves along. That is why such a wave motion is also called a *progressive wave motion.* The progressive movement takes place *through a medium ;* for example, water, rope, springs and air, etc., in the above-mentioned examples of wave motion. Notice that although the disturbance travels from one region of the medium to another, no part of the medium travels very far from its mean position.

Thus, for a wave motion :

(*i*) A material and elastic medium is necessary.

(*ii*) The particles of the medium do not travel forward but simply oscillate about their mean positions.

(*iii*) A particle of the medium begins to oscillate a little later than its preceding particle. In other words the whole of the medium is not disturbed all at once but the motion is handed over from particle to particle.

(*iv*) The velocity of the wave motion is different from the velocity of the vibrating particle of the medium.

6.3 ENERGY TRANSFERRED DURING PROPAGATION OF WAVES

In chapter on "Work and Energy" we discussed the transfer of energy by the bodily motion of masses of material. Winds, tides and projectiles in flight illustrate such energy transfer. Energy may also be transferred by the motion of particles. Electricity and heat are both conducted through metals by the motion of electrons.

Wave motion is a third method of energy transfer. Energy may be transferred through matter (or material medium) by *waves.* A wave originates in displacement of matter from its normal or mean position, which causes some of the material to oscillate about the mean position. The energy disturbance progresses through the matter, but the matter as a whole does not move along the path of the energy.

Let us study some examples of transfer of energy by waves :

(*a*) Drop a stone in a still water tank. Waves (or ripples) will spread from the point where the stone touches the water. As the wave train passes over the surface of water, it does not carry the water with it. This can be seen by placing a piece of some light material such as cork on the surface of water. As the wave passes them, they merely bob up and down. The up and down motion of the piece of cork represents the motion of water molecules at the place occupied by the piece of cork. The fact that the water molecules begin to move up and down indicates that they have received the energy which was created at another place where the stone was dropped. *Thus the wave transfers energy without transferring matter.*

(*b*) If we tie one end of a long string to a hook on a wall and the free end is moved up and down, the disturbance (or a wave) will be seen to travel along the string (Fig. 6.3). The individual points on the string move up or down whereas the hump moves to the left or right. The up and down movement of the points on the string indicates that the points on the string have received energy. In this process there is no transport of matter from the one end of the string to the other but you can see the transfer of energy.

Energy may be transferred through space by *electromagnetic waves*. Light from distant stars travels through the vacuum of outer space as electromagnetic waves. This travelling disturbance is not motion of matter but motion of an electromagnetic field about which you will learn in higher classes.

6.4 PULSES :

Single non-repeated disturbances are called pulses. In other words pulses are waves of short duration. With pulses the medium oscillates for a shortwhile and then returns to its original mean position or equilibrium position. Let us study an example of a pulse (a wave of short duration).

Take a long small-diameter spiral spring or a slinky toy as in Fig. 6.5(*a*), stretched between tworigid supports. Suppose a portion of the spring is displaced by pulling it upward at point 1 to form *a small hump* (or a *crest*), while keeping points 2 and 3 at their original positions [See Fig. 6.5 (*b*)]. When the spring is released, the distorted portion of the spring is pulled back because of the elasticity of the spring. But because of this action of the spring on the region of point 1, the spring in the region of point 3 undergoes a reaction which displaces point 3 upward and the hump moves towards the right as in Fig. 6.5(*c*). Similarly, as the spring in the region of point 3 is pulled back, the spring in the region of point 4 is displaced

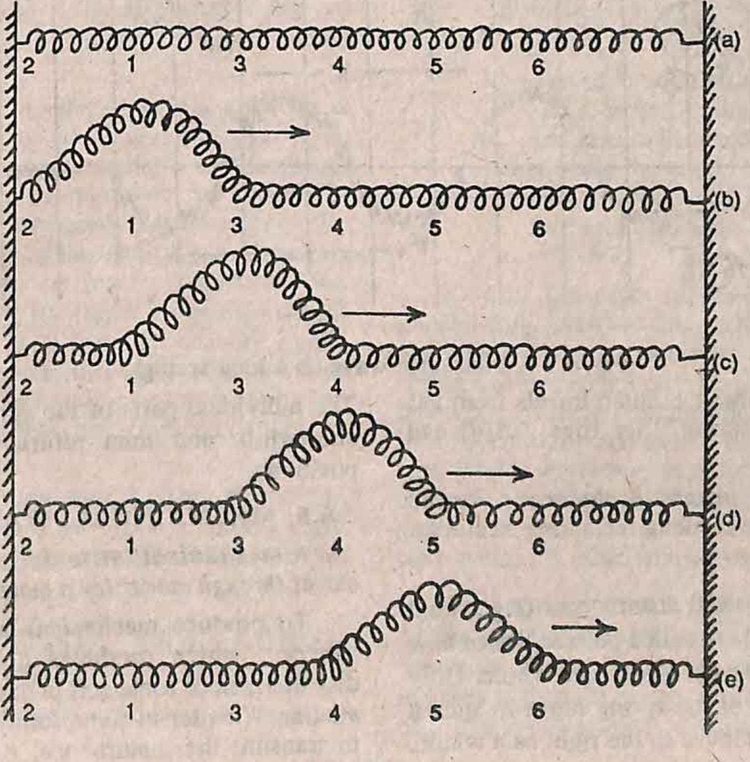


Fig. 6.5

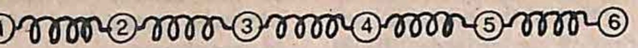


Fig. 6.6

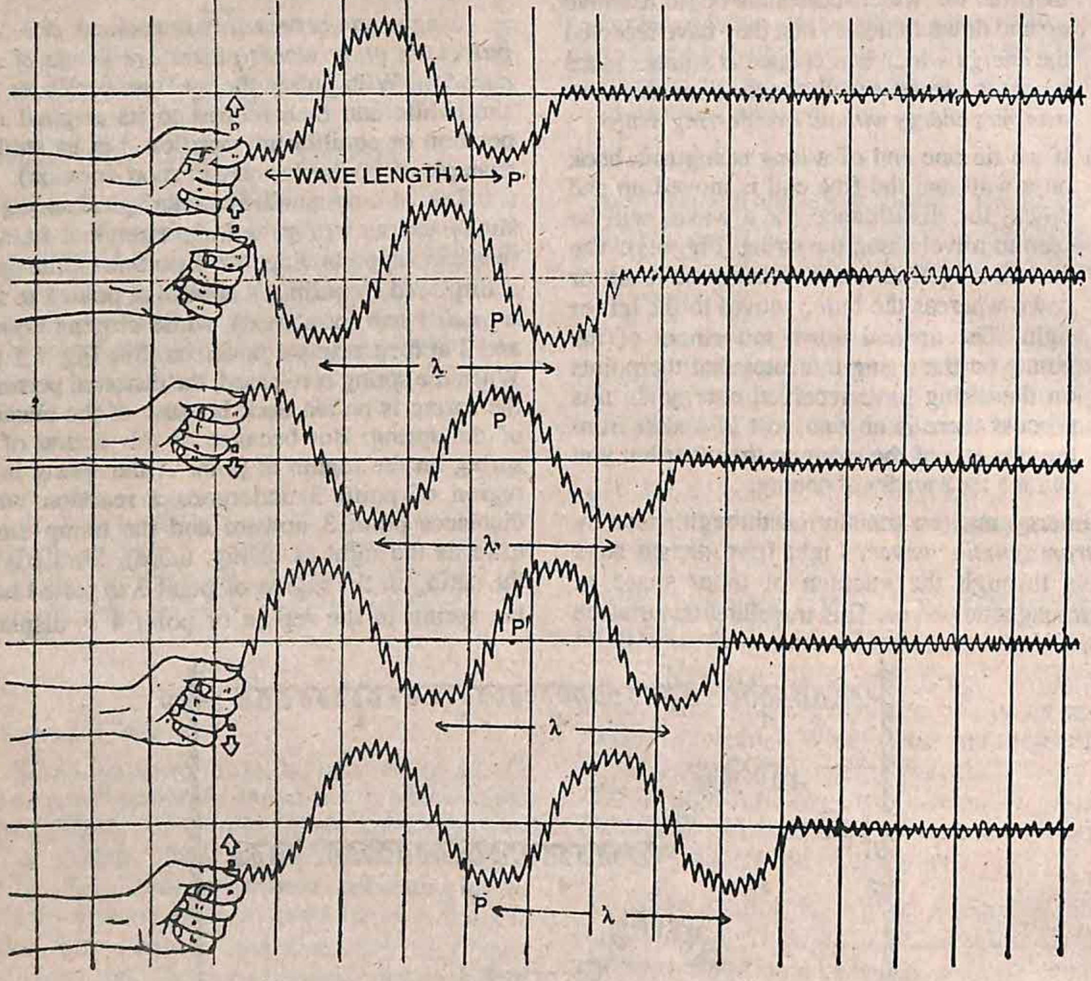


Fig. 6.7 A transverse wave on a long spring.

upward. In this manner the hump travels from left to right along the spring. [See Figs. 6.5(*d*) and 6.5(*e*)].

A *trough* or *downward displacement* formed at point 1 would travel along the spring in similar fashion.

Such single non-repeated disturbances (*e.g.*, small humps in the spring) are called pulses. Notice how the spring itself does not move as a whole. Only the individual parts of the spring move in such a way that the hump moves to the right as a whole. The individual parts of the spring oscillate for a shortwhile and then return to their original positions.

6.5 MECHANICAL WAVES

A mechanical wave is a disturbance that moves through matter (or a material medium).

To produce mechanical waves, we need a *source* which produces a *disturbance* (a displacement of some sort in matter) and an *elastic medium* (matter in some form) which has inertia to transmit the disturbance. An elastic medium

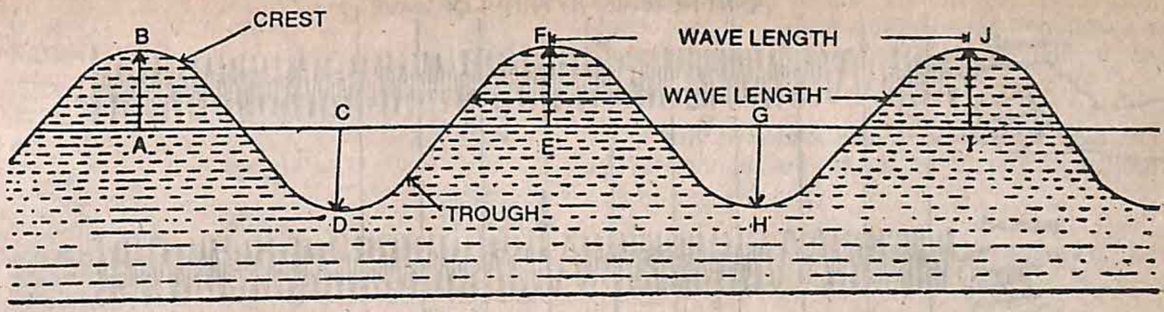


Fig. 6.8 Transverse wave

behaves like an array of particles connected by springs, with each particle at equilibrium (or mean position) (Fig. 6.6). In other words *the medium must be continuous.*

If particle 1 is displaced from its equilibrium position by being *pulled away* from particle 2, it is immediately subjected to a force from particle 2 which attempts to restore particle 1 to its original position. At the sametime, particle 1 exerts an equal but opposite force on particle 2 which attempts to displace it from its equilibrium position. Similar events occur, but in opposite directions if particle 1 is displaced from its equilibrium position by being *pushed towards* particle 2.

If particle 1 is displaced permanently by a source, it exerts a force which displaces particle 2. Particle 2, in turn, being displaced from its equilibrium position, exerts a force on particle 3, which is in turn displaced. In this way, the displacement (a kind of mechanical wave) travels along from particle to particle. Because the particles have inertia, the displacements do not all occur at the same time, but successively as the particles are farther and farther from the source. The kinetic energy imparted to the first particle by the source is transmitted from particle to particle in the medium.

Water waves, waves in a rope, and sound waves are examples of mechanical waves. Light waves are not mechanical waves as they can travel even in a vacuum.

6.6 TRANSVERSE AND LONGITUDINAL WAVES

There are two types of wave motion, namely,

(*i*) Transverse wave motion,and

(*ii*) Longitudinal wave motion.

(*i*) **Transverse wave motion.** *It is a wave motion in which every particle of the medium vibrates harmonically about its mean position in a direction perpendicular to the direction of propagation of the wave.*

Examples are :

(1) Waves on the water surface.

(2) Light, heat and electromagnetic waves.

(3) Vibration of a string under tension in a musical instrument, *e.g.*, a sitar, a guitar, a violin, etc.

(4) Take a long horizontal spring with one end attached to the wall and the other end held in the hand and pulled taut. By moving the hand up and down rapidly two or three times, a wave can be made to travel along the spring as shown in Fig. 6.7.

One of the coils of the spring *P* may be painted (say green) so that its motion can be easily observed. Although the wave travels along the spring in a horizontal direction, *P* oscillates up and down on a verticle straight line and does not move in a horizontal direction. The motion of *P* is, in fact, simple harmonic and the wave is called the transverse wave since the oscillatory motion of any part of the system, such as *P*, is at right angles to the direction in which the wave is travelling.

For transverse waves it is essential that the medium should possess *inertia, elasticity* and *also cohesion*. Transverse waves cannot be propagated in gases as they do not possess cohesion (*i.e.*, force of attraction between the molecules of gases.)

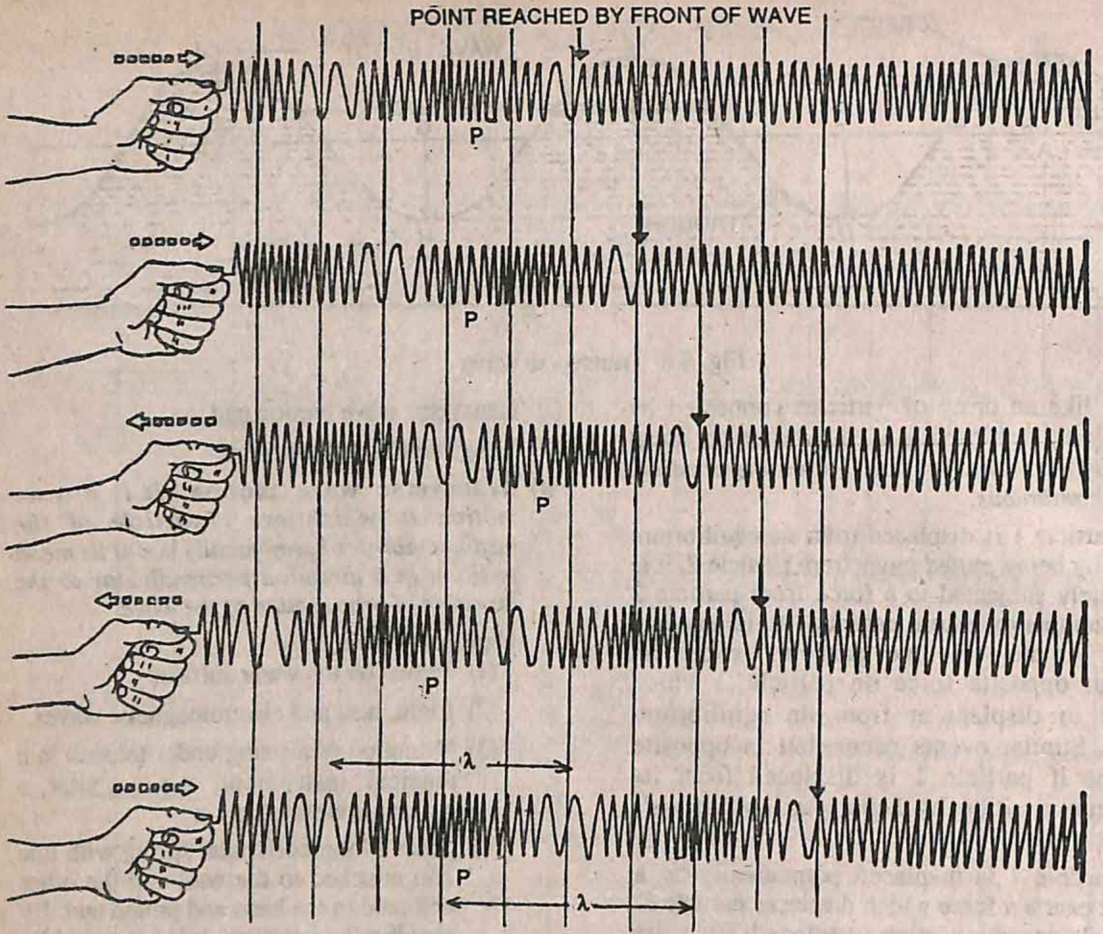


Fig. 6.9

Transverse wave travels in the form of *crests* and *troughs*. Crest is the position of maximum displacement in the positive direction (*e.g.*, *B,F,J*), *i.e.*, above the line of mean position whereas trough is the position of maximum displacement in the negative direction (*e.g.*, *D, H.*), *i.e.*, below the line of mean position as shown in Fig. 6.8.

(*ii*) **Longitudinal wave motion.** *It is a wave motion in which each particle of the medium vibrates harmonically about its mean position in the same direction as the direction of propagation of the wave.*

Examples are :

(*i*) **Compressional waves in springs :**

Take a long horizontal spring and oscillate its free end backward and forward in a horizontal direction (Fig. 6.9). The spring remains straight, but a wave of alternating compressions and extensions travels along its length. The painted (say green) coil *P* performs simple harmonic motion in a horizontal direction. The oscillatory motion of a part of the system is in the same direction that the wave is travelling and so this is a **longitudinal wave.**

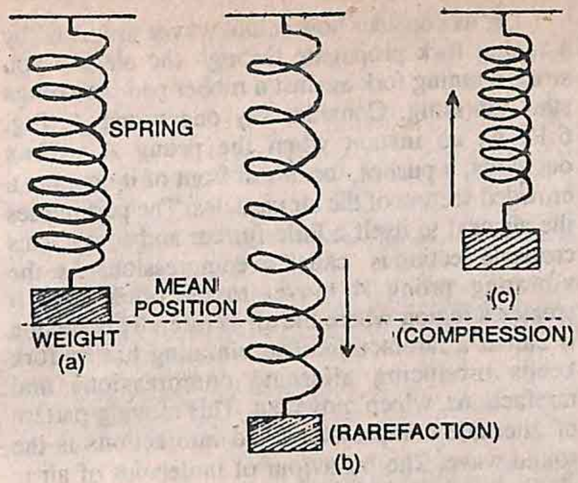


Fig. 6.10

Again consider a spring hung vertically and loaded by a weight at the lower end (Fig. 6.10). When the weight is pulled down and then released, the turns of the spring vibrate up and down along the length of the spring and hence the disturbance is propagated along the spring as a longitudinal wave. When the weight is pulled down, it stretches the spring and hence a few turns of the spring become extended or the distance between them becomes greater than the normal separation. Thus a region of *rarefaction* is caused [Fig. 6.10 (*b*)]. Due to inertia, the weight moves to the position higher than its normal position of rest (*i.e.*, mean position) and this compresses the spring, *i.e.*, a few of the turns become compressed by coming closer together. Thus this state of compression begins to move forward along the length of the spring.

It will be noticed that alternate compressions and rarefactions are formed for sometimes till the weight comes to rest.

(*ii*) Sound in air is another example of longitudinal wave.

Sound is usually transmitted as a longitudinal wave in the air. Consider what happens when you shout to your friend across a lake. Air is expelled from your lungs through your windpipe, past two elastic membranes, known as vocal cords, inside the windpipe (Fig. 6.11). The flow of air past the vocal cords causes them to vibrate, and the size of the opening, between them varies periodically. The air is consequently expelled in *puffs* that follow one another in rapid succession. These puffs of air do not travel all the way across the lake to your friend's ear. As a puff emerges it increases the pressure of the air in the immediate vicinity of the mouth. In between puffs the molecules of air near the mouth move further apart to relieve the excess pressure, but they collide with neighbouring molecules and force them closer together so that a *region of high pressure and density* is created a

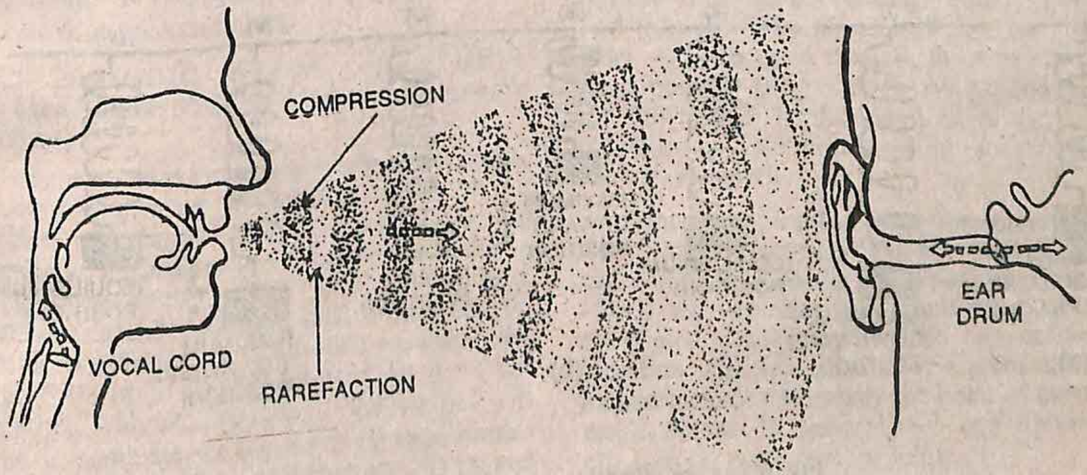


Fig. 6.11 Sound wave in air

little farther from the mouth. In fact the process continues and the region of high pressure moves outward from the mouth with the speed of sound. Each puff creates such a region of high pressure moving outward.

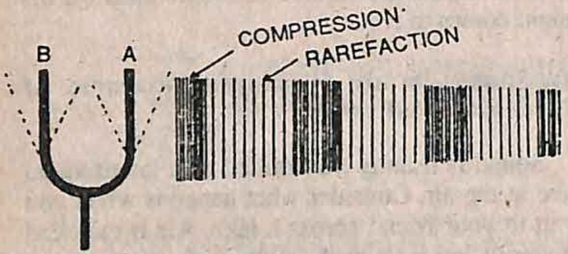


Fig. 6.12

The sound wave therefore consists of a train of high pressure regions (compressions) following one another in rapid succession separated by *regions of lower pressure* (rarefactions) (Fig. 6.12). The individual molecules do not travel with the high pressure regions ; they merely oscillate backward and forward parallel to the direction in which the sound is travelling. *Rather it is energy in the form of an impulse thatpasses from one section of the air to the next.* When these waves reach the ear of a listener, they will vibrate the ear membrane and the listener will hear a sound (Fig. 6.11).

Let us consider how sound waves produced by a tuning fork propagate through the air. As you strike a tuning fork against a rubber pad, its prongs start vibrating. Consider say one prong *A*. Fig. 6.12 At an instant when the prong *A* moves outwards, it pushes the air in front of it creating a crowded section of the air particles. The part pushes the air next to itself a little further and so on. This crowded section is called a compression. As the vibrating prong *A* moves to the other side, it creates a region where the air is rarer. This section is called a rarefaction. The vibrating tuning fork keeps producing alternate compressions and rarefactions, which move out. This moving pattern of alternate compressions and rarefactions is the sound wave. The behaviour of molecules of air is similar to the behaviour of the coils of the spring in Fig. 6.9.

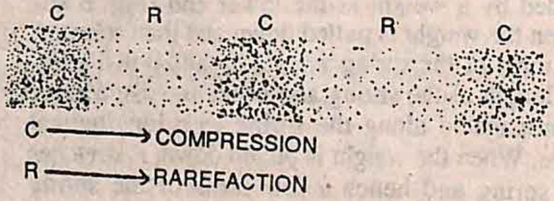


Fig. 6.13

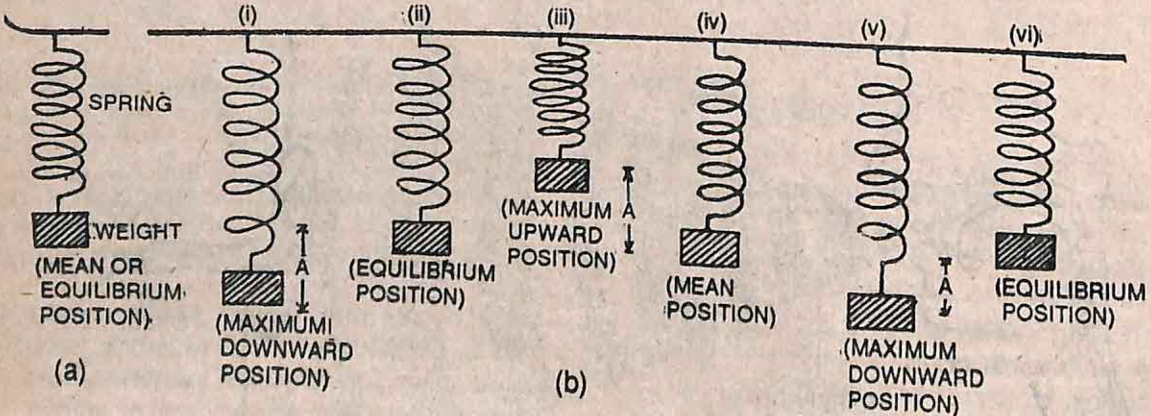

(i)
(ii)
(iii)
(iv)
(v)
(vi)
SPRING
WEIGHT
(MEAN OR EQUILIBRIUM POSITION)
(a)
A
(MAXIMUM DOWNWARD POSITION)
(EQUILIBRIUM POSITION)
(MAXIMUM UPWARD POSITION)
A
(b)
(MEAN POSITION)
A
(MAXIMUM DOWNWARD POSITION)
(EQUILIBRIUM POSITION)

Fig. 6.14 *One vibration of a vibrating weight*

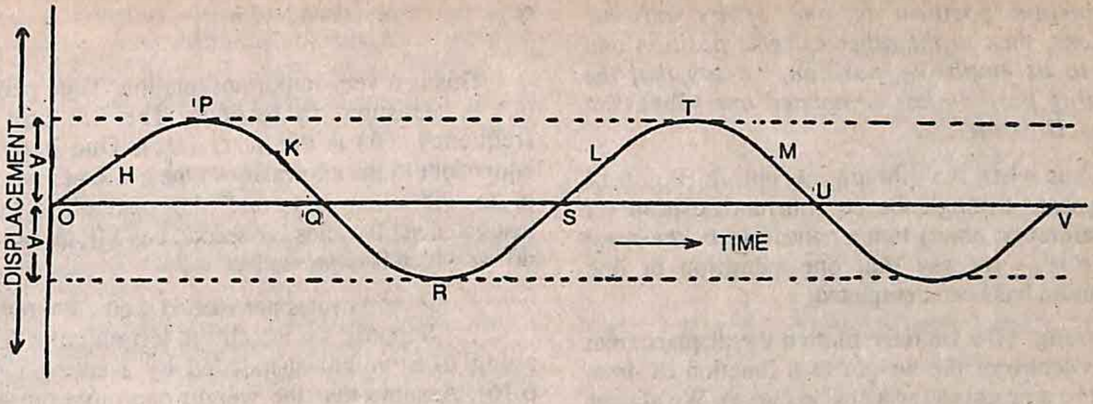


Fig. 6.15 *Diplacement-time curve of a vibrating weight*

Longitudinal waves travel in the form of *compressions* (or *condensations*) and *rarefactions* (Fig. 6.13). Compression is a region of greater density, *i.e.*, the region in which the particles ofthe medium come nearer together than their normal separation whereas rarefaction is a region of smaller density of the medium, *i.e.*, the region in which the particles of the medium are farther than their normal separation.

In a longitudinal wave, due to alternate compressions and rarefactions, the volume of the region of the medium is altered and as such volume elasticity is involved in the process. Hence for longitudinal waves, the medium should possess inertia and elasticity only. That is why this type of wave motion is possible in all the type of media, *i.e.*, solids, liquids and gases.

6.7 PERIODIC WAVES AND THEIR CHARACTERISTICS (*Simple Harmonic Motion*)

So far we have examined the effect of a single, non-recurring wave disturbance. Now let us consider what happens if similar disturbances are repeated periodically. Regular, rhythmic disturbances resulting from continuing periodic vibrations are called *periodic waves*. For example, consider a weight suspended from a vertical spring [Fig. 6.14 (*a*)]. If it is allowed to stand for sometime without disturbance, the weight will come to some steady (or mean or equilibrium) position. If the weight is pulled down slightly and then released, it will start oscillating [Fig. 11.14 (b)]. Such a motion is *periodic* or *simple harmonic motion*. That is, the weight repeats its motion once every certain time interval. The vibrating weight acts as a source of periodic disturbances. The maximum displacement of the centre of the vibrating weight on either side of its mean or equilibrium position is called the **amplitude** of vibration and is usually denoted by A [Fig. 6.14 (*b*)]. The positions of the vibrating weight at different times are shown in Fig. 6.14 (*b*) *i, ii, iii, iv, v, vi*. When released from the position of its maximum downward displacement (Fig. 6.14 (*b*) — *i*), it begins to move up, passes through the equilibrium position (Fig.6.14 (*b*)—*ii*), and continues to move up due to inertia. The upward motion stops when the displacement from the equilibrium position becomes equal to A [Fig. 6.14 (*b*)—*iii*]. The weight will now start moving down again, passes through the equilibrium or mean position [Fig. 6.14 (*b*) *iv*] and stops when the downward displacement is A again [Fig. 6.14(*b*)—*v*]. This motion will go on repeating if there is no friction.

When the weight starting from the maximum downward displacement [Fig. 6.14 (*b*)—*i*], goes up and comes back to the same position [Fig. 6.14 (*b*)*v*], we say that the vibrating weight has completed one vibration. One can define one vibration with reference to any point along the motion and not necessarily the point of maximum displacement. In general, we can define one vibration (or oscillation) as follows :

Whenever a vibrating particle moves from its equilibrium position to one of its extreme positions, then to the other extreme position and back to its equibrium position, we say that the vibrating particle has completed one **vibration** *(or* ***oscillation****).*

Thus when the vibrating weight in [Fig. 6.14 (*b*)] passes through the equilibrium position (or any reference point) twice *travelling in the same direction,* we say that one vibration or one oscillation has been completed.

In Fig. 6.15 we have plotted the displacement of the centre of the weight as a function of time. This is a sine curve (or a cosine curve). We always get such type of curves when we consider vibrating bodies. From Fig. 6.15, it is easy to see that one vibration is completed in each of the following :

OPQRS ; PQRST ; HPKQRSL.

The time taken by a vibrating body to complete one vibration is called its **timeperiod** *(T). The number of vibrations per second is called its* **frequency** *and is denoted by* ν *(Greek letter nu).*

Time period (*T*)

$$= \frac{1}{\text{number of vibrations per second } (\nu)}$$

or $$\boxed{T.\nu = 1}$$

or $$\boxed{\nu = \frac{1}{T}} \text{ and } \boxed{T = \frac{1}{\nu}}$$

This is a very important relation. Time period (*T*) is measured in seconds. The S.I. unit of frequency (ϑ) is the *hertz* (*Hz*). One hertz is equivalent to the expression "One cycle per second or one vibration per second". For example, a wave generated at 60 cycles per second has a frequency of 60 Hz which is expressed as

ν = 60 cycles per second = 60 Hz = 60/s

Suppose we attach the left end of a long string to a weight suspended by a spring (Fig. 6.16). Assume that the weight can move up and down without friction. As the weight moves up and down, a periodic transverse wave travels to the right along the length of the string (Fig. 6.16). If we consider any part of the string, it oscillates up and down while the wave travels to the right, in the form of crests and troughs which replace one another. As a periodic wave travels through a medium (string), the particles of the medium (string) vibrate about their equilibrium positions in identical fashion. However, the particles are in corresponding positions of their vibratory motion at different times. *The position and motion of a particle indicate the* **phase** of the wave. Particles of the medium which have the same displacements and velocities and are moving in the same direction are said to be **in phase.** Particles *O* and *S* ; *P* and *T*; *R* and *N* ; *B* and *D* (Fig. 6.16) are in phase.

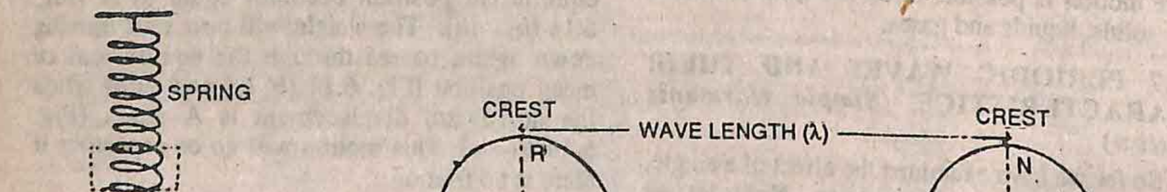


Fig. 6.16 *A wave travelling along a string fastened to an oscillating weight*

Those with opposite displacements and velocities and moving in opposite direction (particles *O* and *Q* ; *P* and *R*) are in **opposite phase** or **out of phase** or **180° out of phase.**

The distance between two consecutive crests or two consecutive troughs along a wave is defined as the **wavelength** and is usually denoted by the Greek letter λ called *lambda*. In Fig. 6.16 , the distance *RN* or *PT* gives the wave length. It is also defined as the distance between two consecutive, vibrating particles which are in the same phase. One crest and one trough also constitute one wave length. *It is also defined as the distance travelled by the disturbance (wave motion) in the time in which the particle of the medium completes one vibration.*

From Fig. 6.16 it is clear that the points separated by distances λ, 2λ, 3λ, ... are all in phase whereas the points separated by distances $\frac{\lambda}{2}$, $\frac{3\lambda}{2}$, $\frac{5\lambda}{2}$, ... are all out of phase.

The amplitude (*A*) of the wave is the same as the amplitude of the oscillating source [*i.e.*, oscillating weight in Fig. 6.16]. As the wave moves forward, each point oscillates with the frequency of the source.

RELATIONSHIP BETWEEN WAVE SPEED, WAVE-LENGTH AND FREQUENCY :

An advancing wave has a finite *speed*, v, for a given transmitting medium. Wave speed may be quite slow, as that of water waves. It may be moderately fast, as that of sound waves in water at room temperature which travel with speeds of the order of $10^2 - 10^3$ ms^{-1}. It may be speed of light or radio-waves 3×10^8 ms^{-1}. The speed of a wave depends primarily on the nature of the wave disturbance and on the medium through which it passes. Wave speed may also depend on *wave-length* in certain media.

When the speed of a wave depends on its wave-length (or frequency) we say the transmitting medium is *dispersive*.

Since a wave travels the distance λ in the time *T* for a complete vibration of the source, its speed (v) is given by the expression

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

$$= \frac{\text{wave-length}}{\text{time-period}}$$

or $$v = \frac{\lambda}{T}$$

But $$\nu = \frac{1}{T} \quad \text{where } \nu \text{ is the frequency.}$$

$$\therefore \text{Speed} = v = \frac{\lambda}{T} = \nu\lambda$$

or $$\boxed{v = \nu\lambda}$$

This shows how fast does a disturbance in a medium travel. This important equation is true for all periodic waves, whether transverse or longitudinal, no matter what the medium is.

As we have shown, the speed of any periodic wave in a medium is equal to the product of its frequency and wavelength. *Note that the speed of the wave and the speed with which any part of the medium oscillates are not at all related.* For one thing the speed of a wave of a given frequency in a medium is constant, whereas the speed of any one part of the medium is constantly changing as it oscillates. The speed is maximum for that part of the medium which is close to its mean position and zero at the extremes of oscillations.

In all forms of travelling waves, energy is transmitted from one point to another. The rate of transfer of energy or the power transmitted by a wave is proportional to the square of the wave amplitude and the square of the wave frequency.

6.8 GRAPHICAL REPRESENTATION OF A PERIODIC WAVE

It is very useful to learn to represent a periodic wave graphically.

(*i*) *Transverse wave* :

Consider a weight, suspended from a vertical spring, to which we attach the left end of a long string (Fig. 6.16). If the weight is allowed to stand for sometime without disturbance, the weight will come to some *steady* or *mean* or *equilibrium* position. Assume that the weight can move up and down without friction. As the weight moves

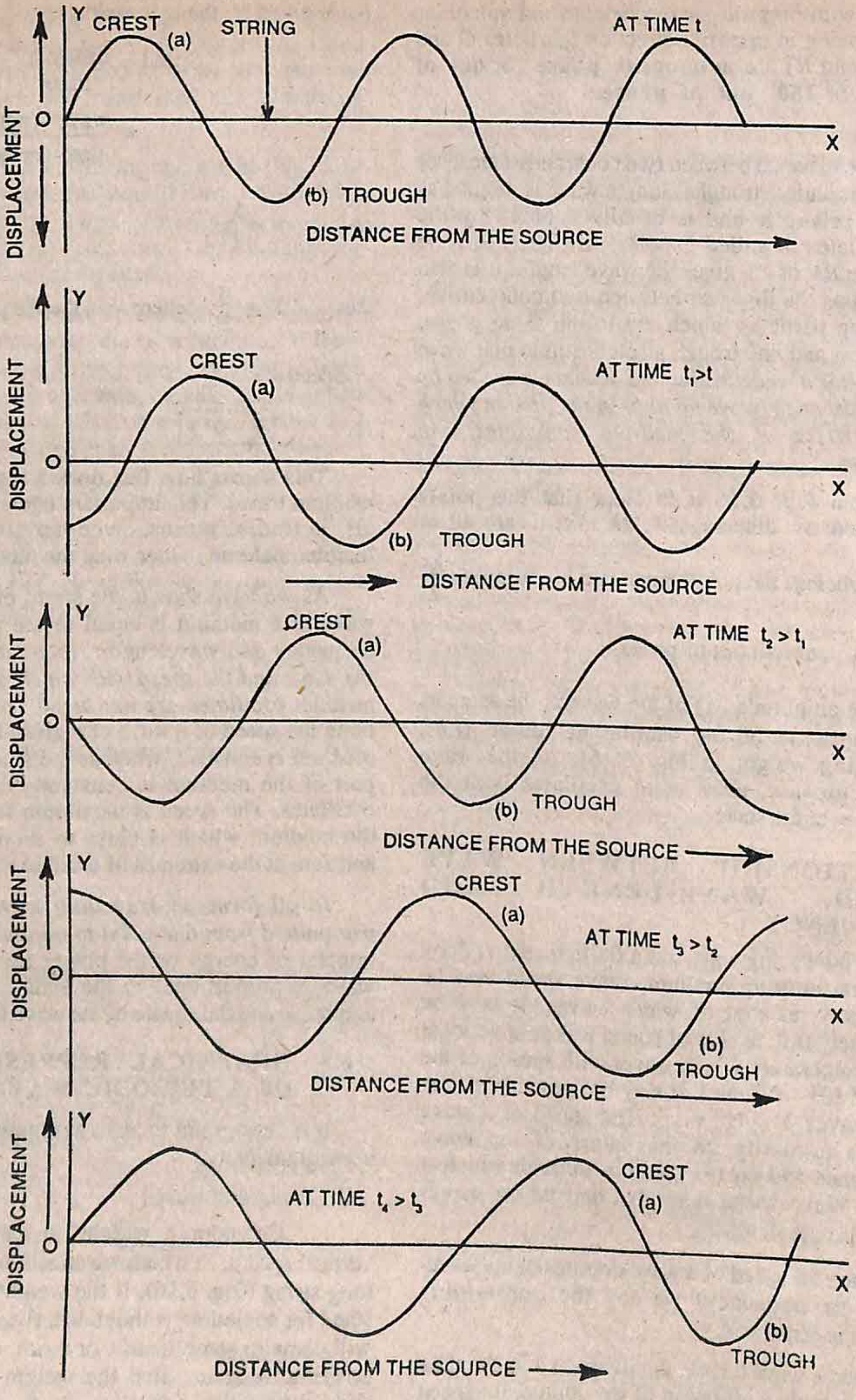

Y
CREST
(a)
STRING
AT TIME t
O
X
(b) TROUGH
DISPLACEMENT
DISTANCE FROM THE SOURCE
Y
CREST
(a)
AT TIME $t_1 > t$
O
X
(b) TROUGH
DISPLACEMENT
DISTANCE FROM THE SOURCE
Y
CREST
(a)
AT TIME $t_2 > t_1$
O
X
(b) TROUGH
DISPLACEMENT
DISTANCE FROM THE SOURCE
Y
CREST
(a)
AT TIME $t_3 > t_2$
O
X
(b)
TROUGH
DISPLACEMENT
DISTANCE FROM THE SOURCE
Y
AT TIME $t_4 > t_3$
CREST
(a)
O
X
(b)
TROUGH
DISPLACEMENT
DISTANCE FROM THE SOURCE

Fig. 6.17

up and down, a periodic transverse wave travels to the right along the length of the string (Fig. 6.16). If we consider any part of the string, it oscillates up and down while the wave travels to the right, in the forms of crests and troughs which replace one another.

Let us say that the string is lying along the X-axis before a transverse wave is generated in it (Fig. 6.17) After a transverse wave is generated in the string, if we plot the displacements of different points of the string *at any instant* along the Y-axis and the distances of those points from the source (*i.e.*, Oscillating weight) along the X-axis, we get a graph as shown in (Fig. 6.17) which represents a periodic transverse wave. The curve is known as *sine* or *cosine curve.*

As time passes new crests and troughs are created at regular time intervals and the pattern repeats itself after a fixed distance. (Fig. 6.17).

Notice how the individual points of the string shift up and down as time increases, and change the shape of the graph. As time increases the crest marked (*a*) and the trough marked (*b*) move to the right.

(*ii*) *Longitudinal wave :*

Let us take the case of a longitudinal wave in a gas. Particles of the gas in the region of compression are in the process of moving forward in the direction of the wave whereas the particles in the region of rarefaction are in the process of moving backward. If the forward displacements are represented by positive ordinate above the straight line (*i.e.*, along Y-axis) and the negative ordinates below that line, the joins of the ends of the ordinates will represent the displacement-time curve as shown in Fig. 6.18. This curve is also known as *sine* or *cosine curve.* This graph represents a periodic longitudinal wave.

For a longitudinal wave, we can also get a similar curve by plotting the *density* of the gas *at any instant* as a function of distance from the source. When no wave travels in the gas, the density of the gas is the same everywhere in the gas. When a longitudinal wave is travelling in the gas, the particle density of the gas changes from a high value at a compression to a low value at a rarefaction. If we plot the density at a point in the gas along the Y—axis against the distance of that point from the source, we get the graph shown in Fig. 6.19 which represents a periodic longitudinal wave.

How is the graph of a periodic wave different from the graph of a pulse ? There are two points of difference :

(*i*) Every point on the string is displaced, unlike a pulse where only a part of the string is displaced from its position. That is, a periodic wave stretches over the entire medium (string).

(*ii*) There is a basic pattern which repeats itself after a fixed distance in case of a periodic wave, which is not so in the case of a pulse which is a sudden and irregular disturbance lasting only for a short duration.

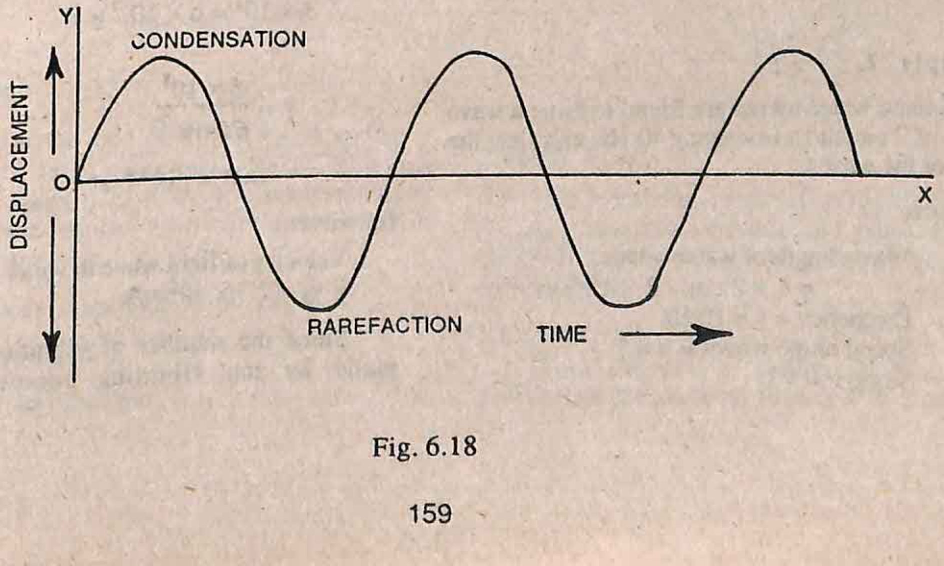


Fig. 6.18

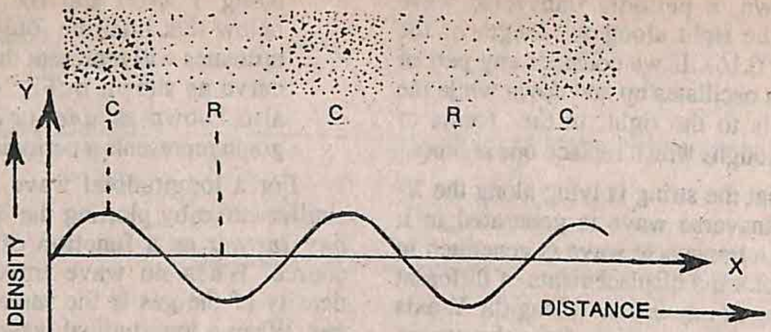


Fig. 6.19

SOLVED EXAMPLES

Example 1.

If the vibrator in a ripple tank strikes the water 200 times in a second, what is the frequency of the waves produced ? If the frequency of the vibrator is halved, what happens to the frequency of the wave ?

Solution :

Frequency of the waves is equal to the frequency of the vibrator. Since the frequency of the vibrator is defined as the number of vibrations made by the vibrator in one second so its frequency is 200 Hz as it makes 200 vibrations in a second.

∴ Frequency of the wave produced

$= 200 \text{ Hz} = 200 \text{ s}^{-1}$

If the frequency of the vibrator is halved, then, the frequency of the wave also gets halved, *i.e.*, 100 Hz or 100 s^{-1}.

Example 2.

If some water waves are found to have a wave length of 2 cm and a frequency 10 Hz, calculate the speed of the waves.

Solution :

Wave length of water waves

$= \lambda = 2 \text{ cm} = 2 \times 10^{-2} \text{ m}$

Frequency $= \nu = 10$ Hz

Speed of the waves $= v = ?$

Since $v = \nu\lambda$

$$\therefore \quad v = 10 \times 2 \times 10^{-2} \text{ m/s} = \mathbf{0.2 \ m/s}$$

Example 3.

Velocity of light in vacuum is 3×10^8 m/s and that in water is 2.3×10^8 m/s. If the wavelength of a wave in vacuum is 6×10^{-7} m, what will be its wavelength in water ? What is the frequency of the wave ?

Solution :

In Vacuum

Velocity of light in vacuum

$= v_1 = 3 \times 10^8$ m/s

Wave length of light wave in vacuum

$= \lambda_1 = 6 \times 10^{-7}$ m

Frequency of the light wave $= \vartheta = ?$

Since $v_1 = \nu\lambda_1$

$\therefore 3 \times 10^8 = 6 \times 10^{-7} \times \vartheta$

$$\therefore \quad \nu = \frac{3 \times 10^8}{6 \times 10^{-7}} = \mathbf{5 \times 10^{14} \ s^{-1}}$$

In water

Velocity of light wave in water

$= v_2 = 2.3 \times 10^8$ m/s

Since the number of vibrations per second made by the vibrating source of light is independent of the medium in which it is vibrating, its frequency in vacuum is the same as that in water.

Hence, frequency of the light wave in water

$= \nu = 5 \times 10^{14}\ s^{-1}$

Wave length of the light wave in water

$= \lambda_1 = ?$

Since $v_2 = \nu \lambda_2$

$\therefore\ 2.3 \times 10^8 = 5 \times 10^{14}.\lambda_2$

$$\text{or} \quad \lambda_2 = \frac{2{\cdot}3 \times 10^8}{5 \times 10^{14}}$$

$$= \mathbf{4.6 \times 10^{-7}\ m}$$

Example 4.

If a tuning fork vibrates with a frequency of 512 Hz to produce sound waves which travel with a velocity of 330 m/s, find the wave length.

Solution :

Frequency of the tuning fork = ϑ = 512 Hz.

This is also the frequency of the sound waves.

Velocity of sound waves = v = 300 ms^{-1}

Wave length of sound waves = λ = ?

Since $v = \nu\lambda$

$$\therefore\ \lambda = \frac{v}{\nu}$$

$$= \frac{330}{512}$$

$$= \mathbf{0.645\ m}$$

Example 5.

A mass at the end of a horizontal spring is stretched 0.10 m from its rest position and then released. It takes 0.75 s for the mass to move through its rest position to its extreme position in the opposite direction.

(*a*) What is the amplitude of the motion ?

(*b*) What is its period ?

(*c*) What is its frequency ?

Solution :

(*a*) Since the amplitude is the maximum displacement, so the amplitude of the motion

$$= A = \mathbf{0.10\ m}$$

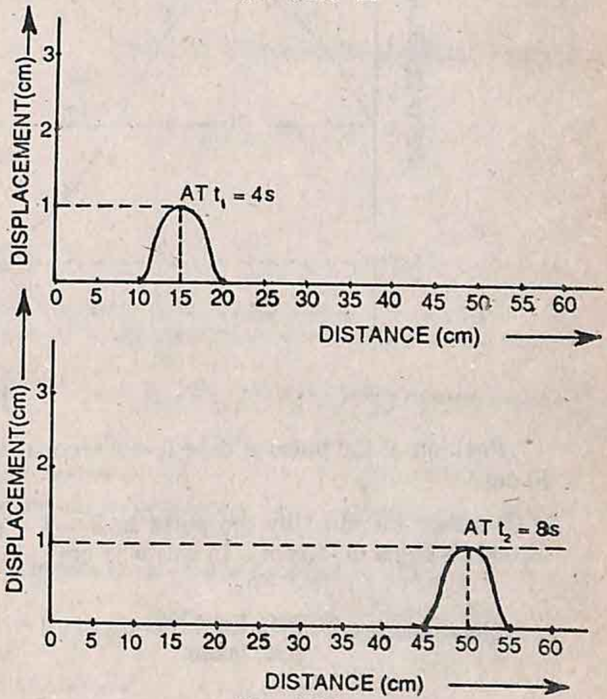


Fig. 6.20

(*b*) Since it takes 0.75 s for the mass to make a one-way trip from one side to the other, the time for a round trip will be 2 × 0·75 = 1·5 s. Hence time period (*T*) = **1.5 s**

$$(c)\ \text{Frequency}\ (\nu) = \frac{1}{T}$$

$$= \frac{1}{1.5}\ s^{-1}$$

$$= \mathbf{0.67\ s^{-1}\ \text{or}\ 0.67\ Hz}$$

Example 6.

The following graph (Fig. 6.20) shows the displacement versus distance of a pulse on a rope at two different times. Find the speed of the pulse and its amplitude.

Solution :

From the graph in Fig. [6.20], we have position of the pulse at time t_1 = 4 seconds is 15 cm.

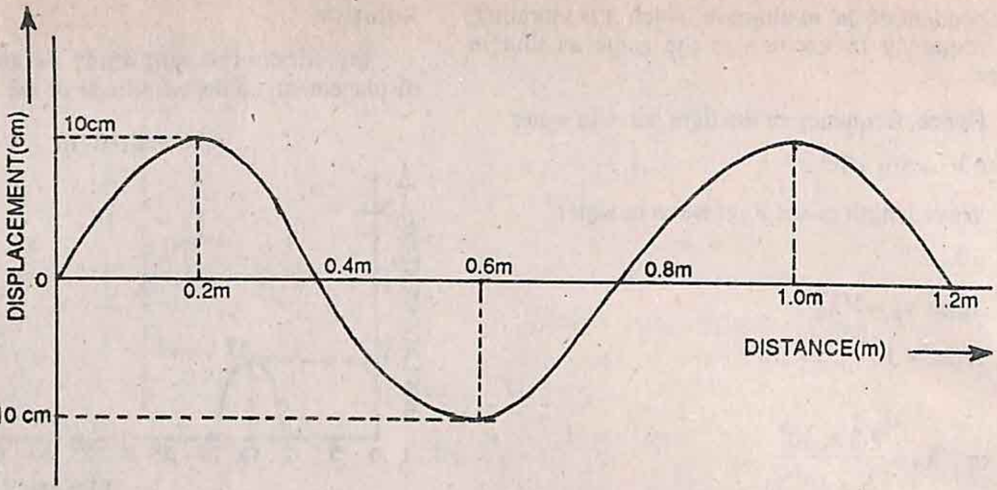


Fig 6.21

Position of the pulse at time $t_2 = 8$ seconds is 50 cm.

∴ Distance travelled by the pulse in $8 - 4 = 4$ seconds is equal to (50 cm – 15 cm) = 35 cm

$$\text{Since, speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

$$\text{So, the speed of the pulse} = \frac{35\ \text{cm}}{4\ \text{second}}$$

$$= \mathbf{8.75\ cm/s}$$

Amplitude (A) of the pulse = maximum height of the graph

$= \mathbf{1\ cm}$.

Example 7.

Fig. 6. 21 shows the shape of a part of a long string in which transverse waves are produced by attaching one end of the string to a vibrator of frequency 500 Hz. Determine (*i*) the amplitude, (*ii*) the wavelength, and (*iii*) the speed of the waves.

Solution :

(*i*) Amplitude (A) of a wave is defined as the maximum displacement of the wave on either side of its mean position. From the Fig. 6.21 it is clear that the amplitude of the waves is **10 cm** or **0.1m**.

(*ii*) Wavelength (λ) of a wave is the distance between the centres of *two consecutive crests or troughs*. One crest and one trough also constitutes one wavelength.

∴ Wavelength (λ) of the waves from Fig. 6.21
$= 1.0\ \text{m} - 0.2\ \text{m}$
$= \mathbf{0.8\ m}$.

(*iii*) Frequency of the wave is the same as the frequency of the vibrator.

∴ Frequency of the wave (ϑ) = 500 Hz (Given)
Wavelength of the wave = $\lambda = 0.8$ m
∴ speed of the wave (v) = $\nu\lambda$
$= 500 \times 0.8$ m/s
$= \mathbf{400\ ms^{-1}}$

Example 8.

A boat at anchor is rocked by waves whose crests are 100 m apart and whose velocity is 25 m/s. How often do the crests reach the boat ?

Solution :

Given,

Distance between two consecutive crests = wavelength (λ)

= 100 m

Velocity of the wave (v) = 25 m/s

Frequency (ν) of rocking of the boat = ?

Since,

$$v = \nu \lambda$$

$$\therefore \nu = \frac{v}{\lambda}$$

$$= \frac{25}{100} \text{ Hz}$$

$$= \boxed{0.25 \text{ Hz}}$$

Thus, the frequency of rocking of the boat is 0.25 Hz.

As, timeperiod (T) = $\frac{1}{\nu}$

$$\therefore \quad T = \frac{1}{0.25} = 4 \text{ seconds}$$

Thus the crests reach the boat every 4 seconds.

SUMMARY

1. Wave motion is a *disturbance* in the medium due to repeated, periodic and to and fro motion of the particles of the medium about their mean position. The whole of the medium is not disturbed all at once but the motion is handed over from one particle to another.
2. Wave is a method of *energy propagation* through space which involves periodic variations in the medium through which the wave travels.

   Thus waves transport energy and not matter.
3. A pulse is a disturbance which is sudden and lasts for a short duration of time.
4. *Mechanical waves* are those waves which require a material medium for propagation, *e.g.*, water waves, sound waves. Light waves are not mechanical waves.
5. *Longitudinal* wave : The particle motion is *parallel* to the direction of the wave, *e.g.*, sound wave in air .
6. *Transverse wave :* The particle motion is *perpendicular* to the direction of the wave, *e.g.*, light wave, ripples in water.
7. *Periodic motion :* Motion which repeats itself after a fixed time interval.
8. *Time-period* (T) : The time interval during which a physical system completes one full cycle of motion.
9. *Frequency* (ν) : The number of vibrations (or complete cycles) per second.

   $$\boxed{\nu = \frac{1}{T}}$$

   Its unit in S.I. system is *hertz* (Hz)
10. *Displacement :* The distance of a moving system from its equilibrium position at some instant of time.
11. *Amplitude* (A) : It is the maximum value of the displacement.
12. *Wavelength* (λ) : The distance between any two consecutive points on a wave pattern which are in *the same phase*. It is also the distance travelled by the wave in a medium in a time during which a vibrating particle of the medium completes one full vibration.

    In a transverse wave, one crest and one trough constitute one wavelength while in a longitudinal wave one condensation (or compression) and one rarefaction constitutes one wavelength.
13. *Speed of a wave :*

    Speed of a wave = frequency × wavelength

    $$\boxed{v = \nu \lambda}$$

    $$\boxed{\text{or } v = \frac{\lambda}{T}}$$
14. *Crest* in a transverse wave is a point at maximum displacement *above* its mean position (or equilibrium position).
15. *Trough* in a transverse wave is a point at the maximum displacement *below* its mean (or equilibrium) position.
16. *Compression* or *condensation* in a longitudinal wave is a region where the particles of the medium come closer together. In this region, the *density* or *pressure is greater than the normal.*

17. *Rarefaction* in a longitudinal wave is a region where the particles of the medium go farther apart. In this region, the density or pressure is *less* than the normal.

18. A *periodic wave* is a disturbance which is caused in a medium by a continuous and periodic oscillatory motion of the particles of the medium.

The *characteristics* of a periodic wave are its amplitude, time-period, frequency, wavelength and velocity.

QUESTIONS

[A] Objective — Type Questions

1. In wave motion, a single disturbance which is not repeated is known as
   - (*a*) peak
   - (*b*) pulse
   - (*c*) transverse wave
   - (*d*) longitudinal wave.
2. A wave in which the particles of the medium vibrate at right angles to the direction in which the energy travels is known as
   - (*a*) a pulse
   - (*b*) electromagnetic
   - (*c*) transverse
   - (*d*) compressional
3. A sound wave in air is
   - (*a*) longitudinal
   - (*b*) transverse
   - (*c*) torsional
   - (*d*) electric
   - (*e*) partly longitudinal, partly transverse.
4. Pranav holds on to one end of a stretched spiral spring, Ashish to the other, Arun pinches several coils close together. This distortion is known as a
   - (*i*) trough
   - (*ii*) crest
   - (*iii*) rarefaction
   - (*iv*) compression.
5. A tuning fork vibrates in air. The number of compressions going past a given point per second is the
   - (*a*) wavelength
   - (*b*) time-period
   - (*c*) frequency
   - (*d*) amplitude
   - (*e*) phase.
6. Rinku produces a certain note (sound of a certain frequency) when she strikes a tuning fork gently. If she strikes the tuning fork harder, the most probable change will be that the sound wave will
   - (*a*) travel faster,
   - (*b*) have a higher frequency,
   - (*c*) have a greater amplitude, or
   - (*d*) have a longer period.
7. At a given temperature, all sound waves in air have the same
   - (a) frequency

- (*b*) speed
- (*c*) time-period
- (*d*) amplitude

8. If the frequency of vibration of an object producing sound in air is increased the characteristic of the sound wave which must change is the

- (*a*) amplitude
- (*b*) speed
- (*c*) wavelength
- (*d*) intensity.

9. The speed of certain water waves is 5 m/s. If its wavelength is 2 m, its frequency is ————.

10. A sound wave in air has a frequency of 500 Hz. Its period is ————.

11. If the speed of sound in air is 350 ms^{-1} and its frequency is 1000 Hz, the wavelength is ————

12. One wavelength is the distance between ————.

13. Velocity of a wave × time-period = ————.

14. In Fig. 6.22, one wavelength is the distance between point A and point ————.

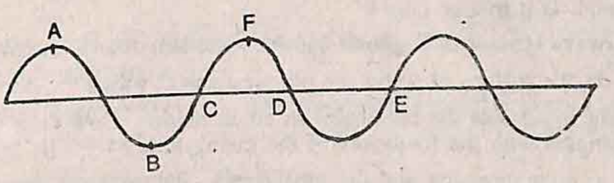


Fig. 6.22

15. The wavelength of a 5000 Hz sound wave having a speed of 5.9×10^3 ms^{-1} in steel is about

- (*i*) 1 μm
- (*ii*) 1 mm
- (*iii*) 1 cm
- (*iv*) 1 m
- (*v*) 1 km

16. Waves transfer something from one place to another. That something may be

- (*a*) mass,
- (*b*) velocity,
- (*c*) energy
- (*d*) wavelength.

17. S.I. unit of frequency is

- (*i*) hertz
- (*ii*) s^{-2}
- (*iii*) cycles per second
- (*iv*) s^{-1}

18. In a transverse wave (Fig. 6. 22), the distance between a crest A and the next trough B is 10 cm. What is the wavelength of the wave ?
   (*i*) 5 cm
   (*ii*) 10 cm
   (*iii*) 20 cm
   (*iv*) 40 cm.

[B] Very Short Answer — Type Questions

1. Is a wave a disturbance or energy ?
2. What is a pulse ?
3. Give S.I. Unit of frequency of a wave.
4. What is the unit of wavelength in S.I. system ?
5. How is frequency of a wave related to its time-period ?
6. What are the two common classifications of waves ?
7. What kind of a wave is sound ?
8. What kind of a wave is light ?
9. Name the kind of wave in case of a ripple.
10. How is the velocity of wave related to its frequency and wavelength ?
11. What is the frequency of a wave whose timeperiod is 0.002 s ?
12. Sound travels in vacuum. Is it true or false ?
13. The time-period of a wave motion is 1 second and its wave-length is 5 cm. What is its velocity ?
14. Is it true that ripples on the surface of water are not mechanical waves ?
15. A tuning fork vibrating in air sets the molecules in air in motion. How does the frequency of vibration of these molecules compare with the frequency of the tuning fork ?
16. In a longitudinal wave, a compression and the next rarefaction are 3 cm apart. What is the wavelength of the wave ?
17. How many vibrations per second are represented in a wave of 101 MHz ?
18. As the frequency of a wave of constant speed is increased, does the wave-length increase or decrease ?
19. In what direction are the vibrations compared to the direction of wave travel in a transverse wave ?

[C] Short Answer — Type and Essay — Type Questions

1. What evidence can you think of to show that a wave transmits energy ?
2. What is the difference between a pulse and a periodic wave ? Give an example.
3. Define wave-length of a wave.
4. (*a*) Define wave motion. Give two examples of wave motion.
   (*b*) Distinguish between a transverse wave and a longitudinal wave. Give two examples of each.
   (*c*) How does the motion of the particles of a medium differ from the motion of the wave through it?
5. Define the following terms with reference to a wave motion :
   A complete oscillation (or vibration); time-period; frequency; amplitude; wave-length.
6. Derive the relationship between the time-period and frequency of a wave.
7. Derive the relationship between wave-length, frequency and the velocity of a wave.
8. Explain the following terms in relation to a wave :
   (*i*) Compression (or Condensation),
   (*ii*) Rarefaction,

(*iii*) Crest, and

(*iv*) Trough.

9. What is a wave motion ? Mention its characteristics.
10. In what ways may energy be transferred ?
11. What is a disturbance ? What constituted the disturbance when a wave moves across the surface of a pond ? What constitutes the disturbance when a longitudinal wave travels through the air ?
12. What does a wave source supply to the medium through which the wave passes ?
13. What kind of a wave is sound ? What variables can be used to represent a sound wave as a sine curve ?
14. How do transverse waves differ from longitudinal waves ? Describe an experiment which can distinguish between the two.
15. When a wave is generated in a pond, is it the water or the wave or both which travel ? Describe an experiment to support your answer.
16. (*a*) Is sound wave in air a transverse wave or a longitudinal wave ?
    (*b*) How will you explain the propagation of a sound wave in air ?
17. The steam of a railway engine is seen first and the whistle is heard a little later. Why ?
18. A tuning fork is marked with the number 512. What does this number signify ?
19. Why cannot a mechanical wave travel through vacuum ?
20. What is a mechanical wave ? How is it produced ?
21. What are periodic mechanical waves ?
22. What is a pulse ? How will you produce a transverse pulse in a spring and a longitudinal pulse in a spring ?
23. What is a periodic wave ? How will you demonstrate the generation of (*i*) a periodic transverse wave, and (*ii*) a periodic longitudinal wave ?
24. How will you represent *graphically* (*a*) a transverse wave, and (*b*) a longitudinal wave ?
25. What is the source of all waves ?
26. Distinguish between sound waves and light waves.
27. How is a sine curve related to a wave ?
28. Exactly what is it that moves from source to receiver in wave motion ?
29. Does the medium in which a wave moves travel along with the wave itself ? Give examples.
30. How do compressions and rarefactions of longitudinal waves compare to crests and troughs of transverse waves ?
31. (*a*) How far does a wave travel during one period ?
    (*b*) How does the frequency of vibration of a small object floating in water compare to the number of waves passing it each second ?

PROBLEMS

1. The velocity of sound in seawater is 1531 m/s. Find the wavelength in seawater of a sound wave whose frequency is 256 Hz.
   [Ans. 5.98 m]
2. A tuning fork vibrating at 300 Hz is placed in a tank of water. (*a*) Find the frequency and wavelength of the sound waves in the water. (*b*) Find the frequency and wavelength of the sound waves produced in the air above the tank by the vibrations of the water surface. The velocity of sound is 1498 m/s in water and 331 m/s in air.
   [Ans. (*a*) 300 Hz; 4.99 m (*b*) 300 Hz; 1.10 m]
3. The velocity of sound waves in air at sea level is 331 m/s. Find the wavelength in air of a sound wave whose frequency is 440 Hz.
   [Ans. 0.75 m]

4. A tuning fork vibrating at 600 Hz is immersed in a tank of water, and the resulting sound waves in the water are found to have a wavelength of 2.5 m. What is the velocity of sound in the water ?

[Ans. 1500 m/s]

5. Velocity of sound in air is 330 m/s. What will be the wavelength of sound of frequency (*i*) 20 Hz, (*ii*) 20000 Hz, (*iii*) 50000 Hz and (*iv*) 120000 Hz.

[Ans. (*i*) 16.5 m; (*ii*) 1.65 cm (*iii*) 0.66 cm (*iv*) 0.275 cm]

6. The measured time interval between our seeing the lightning and our hearing the thunder is 5 seconds. What is the distance of cloud from us ? Velocity of sound in air is 333.3 m/s.

[Ans. 1.7 km]

7. Calculate the time taken by wave to travel a distance of 100 km. Velocity of wave is 3×10^8 m/s

[Ans. 3.3×10^{-4} s]

8. A man sets his watch by the noon whistle of a factory at a distance of 1 km. How many seconds is his watch slower than the time piece of the factory ? Velocity of sound in air = 322 m/s.

[Ans. 3.01 s]

9. If the period of small ripples on water is 0.1 s and their wave length is 5 cm, what is the speed of the waves ?

[Ans. 0.5 m]

10. What is the speed of a wave motion, which has frequency 2.5 Hz and wavelength 0.60 m ?

[Ans. 1.5 m/s]

11. Calculate the wavelength of water waves which have frequency 0.50 Hz and speed 4.0 ms^{-1}.

[Ans. 8 m]

12. The speed of transverse waves in a string is 15 ms^{-1}. If a source produces a disturbance, frequency 5.0 cycles/s, what is the length of the waves produced ?

[Ans. 3 m]

13. A series of periodic transverse waves, frequency 10.0 Hz, travels along a string. The distance between a crest and either adjacent trough is 1.50 m. What is (a) the wavelength, (b) the speed of the wave motion ?

[Ans. (a) 3 m (b) 30 ms^{-1}]

Hints :

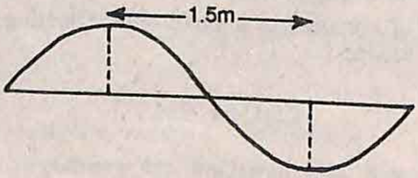


Fig. 6.23

14. Periodic longitudinal waves, frequency 20 Hz, travel along a coil spring. If the distance between successive compressions is 0.40 m, calculate the speed of the wave motion.

[Ans. 8 ms^{-1}]

15. What is the wavelength of periodic longitudinal waves in a coil spring, frequency 8.0 Hz and speed 20.0 ms^{-1} ?

[Ans. 2.50 m]

16. What is the time period of a wave of frequency 500 Hz ?

[**Ans.** 0.002 s]

17. The time-period of a vibrating body is 0.01 second, what is the frequency of the wave it emits ?

[**Ans.** 100 Hz]

18.

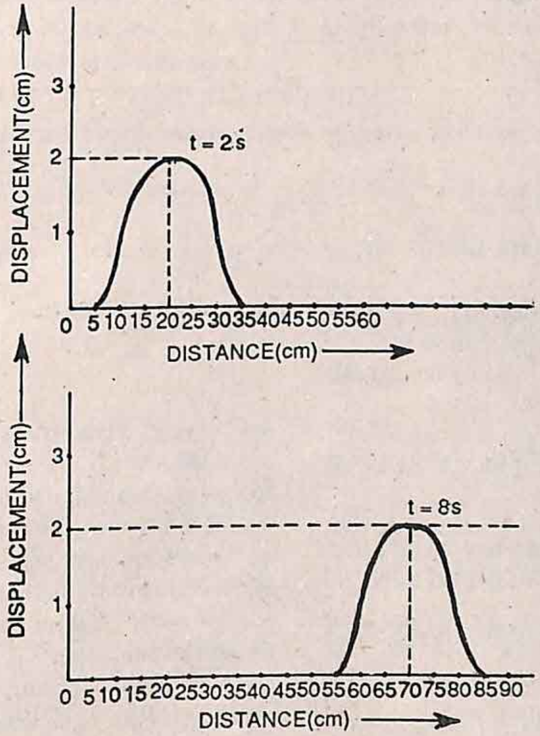


Fig. 6.24

The above graph Fig. 6.24 shows the displacement versus distance of a pulse on a rope at two different times. Find the speed of the pulse and its amplitude.

[**Ans.** 8.3 cms^{-1}; 2 cm]

19. A wave generator generates 16 pulses in 4.0 seconds : (a) What is its period ? (b) What is its frequency ?

[**Ans.** (a) 0.25 s (b) 4 pulses/s]

20. One pulse is generated every 0.10 s in a tank of water and the wavelength of the surface wave measures 3.3 cm. What is the propagation speed ?

[**Ans.** 33 cms^{-1}]

21. A body vibrating with a certain frequency sends waves 0.15 m long through a medium A, and 0.20 m long through a medium B. The velocity of wave in A = 120. cm/s. Find the velocity of wave in B.

[**Ans.** 1.6 m/s]

22. A mass at the end of a horizontal spring is stretched 0. 050 m from its rest position and then released. If it takes 1.0 s for the mass to move through its rest position to an extreme position in the opposite direction,

(a) What is the amplitude of the motion ?

(b) What is the frequency of the vibration ?

[**Ans.** (a) 0.050 m (b) 0.50 Hz]

23. A wave has a wavelength of 4 m and frequency of 200 Hz. Find its time period and velocity.

[**Ans.** 0.005 second ; 800 ms^{-1}]

24. What is the period of a sound wave with a frequency of 2.5×10^3 Hz ?

[**Ans.** 4×10^{-4} s]

25. What is the frequency of a light wave with a period of 1.6×10^{-15} s ?

[**Ans.** 6.25×10^{14} Hz]

❑ ❑

CHAPTER –7

LIGHT

Learning Objectives :

At the completion of this Chapter, you should be able to grasp :

1. that light waves carry energy and how is it being perceived by the human eye ;
2. the structure and function of human eye ;
3. the formation of image by the eyelens on the retina ;
4. the causes of myopia and hypermetropia- defects of vision and the ways to correct these defects of vision ;
5. the perception of colour- composition of white light and that different colours have different wavelengths ;
6. the reasoning of colour of objects ; colour sensory cells in the eye-rods and cones blind spot and colour blindness ;
7. the construction and working of telescopes and microscopes- (qualitative analysis only).

7.1

INTRODUCTION

Light is radiation that can produce the sensation of sight. *Light is a form of energy.* The sun, the stars, electric light bulbs, fluorescent lights, sodium vapour and mercury vapour lamps and many other things emit light. Highly polished surface sends back most of the light that falls on it in a definite direction while light is scattered by a rough surface. When light is absorbed by a black oil, the temperature of the oil rises. Special type of curved mirror gives enlarged image as well as diminished image while the plane mirror does not.

You have learnt in earlier classes that light can pass through air, through a vacuum and through transparent and translucent substances. Any thing through which light passes is known as a medium. You already know, also that in each of these media light travels in a straight line. You have also learnt in earlier classes that when light goes from one *medium* to another, it gets its path changed *(refraction of light)*. You will see in this Chapter how important is it to study this effect on the path of light, as on it depend most of the optical instruments we use everyday *e.g.*, spectacles, telescopes, microscopes, the human eye etc.

Experiments have proved beyond doubt that white light is composed of seven colours and when white light passes through a prism each colour bends to a different extent. Bodies (opaque or transparent) do not have any colour of their own. The colour of the body depends on the *nature* of the incident light and the selective reflection or transmission of the different colours by the body.

Let us find answers to such type of questions in this Chapter.

7.2

REFLECTION BY SPHERICAL MIRRORS

(Revision only)

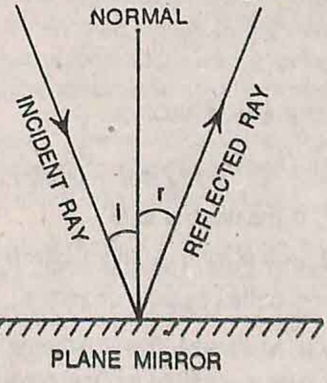
You have already studied the laws of reflection (as given below) in your earlier classes :

Laws of reflection :

(1) The angle of incidence *i* is equal to the angle of reflection *r*. (Fig. 1.7).

(2) The incident ray, the normal to the surface at the point of incidence, and the reflected ray lie in one and the same plane.

The laws of reflection that hold good for a plane mirror, are also applicable in the case of a spherical mirror.



(Laws of Reflection)

Fig. 7.1.

You have also learnt in your earlier classes the definitions of various terms related to spherical mirrors and how to draw ray diagrams to obtain images formed by spherical mirrors for objects placed at different positions. As a *revision work*, a *summary* of the definitions of terms related to spherical mirrors ; drawing of ray diagrams for spherical mirrors and images formed by a concave mirror and a convex mirror is given below :

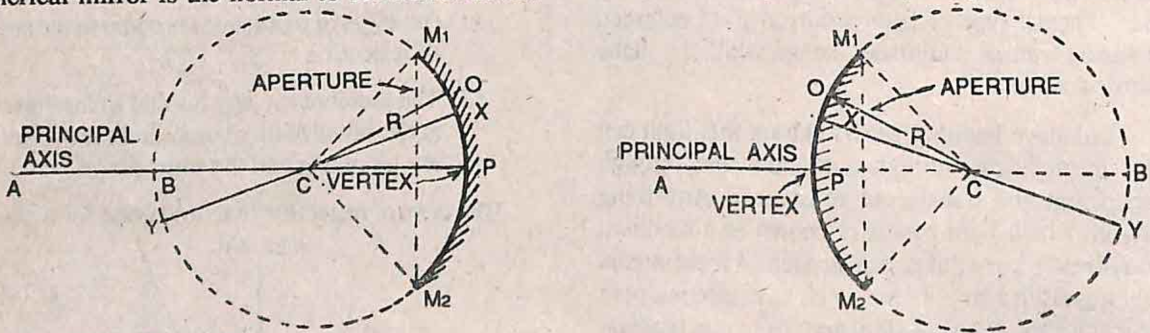
Spherical mirrors :

A spherical mirror is a part of a hollow sphere or a spherical surface whose one side is silvered and other side is polished (Fig. 7.2). It is either **concave** or **convex**, according as the reflecting surface is towards, or away from, the centre of the sphere of which it forms a part. Certain physical terms relating to the spherical mirrors are defined below (See Fig. 7.2) :

Centre of Curvature. The centre of curvature, C, is the centre of the sphere of which the spherical mirror forms a part.

Radius of Curvature. The radius of curvature is the radius OC or PC of the sphere of which the spherical mirror is a part.

Normal. A radius drawn through a point on the spherical mirror is the normal to the mirror at that point. OC is the normal at O.



(A) CONCAVE MIRROR

(B) CONCAVE MIRROR

Fig. 7.2 Circular Sections of spheres from spherical mirrors

Vertex or Pole. The mid-point, P, of the spherical mirror is called its pole or vertex.

Linear Aperture. The diameter, M_1M_2, of the spherical mirror is called its linear aperture.

Angular Aperture. The angle M_1CM_2 subtended by the diameter of a spherical mirror at its centre of curvature is called its angular aperture.

Principal Axis. The straight line, PCB, passing through the vertex, P, and the centre of curvature, C, of a spherical mirror is called its principal axis.

Secondary Axis. Any straight line, XY, other than the principal axis, passing through C, the centre of curvature of a spherical mirror, is called a secondary axis of the mirror.

Principal Section. A section of the spherical mirror cut by a plane passing through its centre of curvature and the pole is called a principal section. It contains the prinicipal axis.

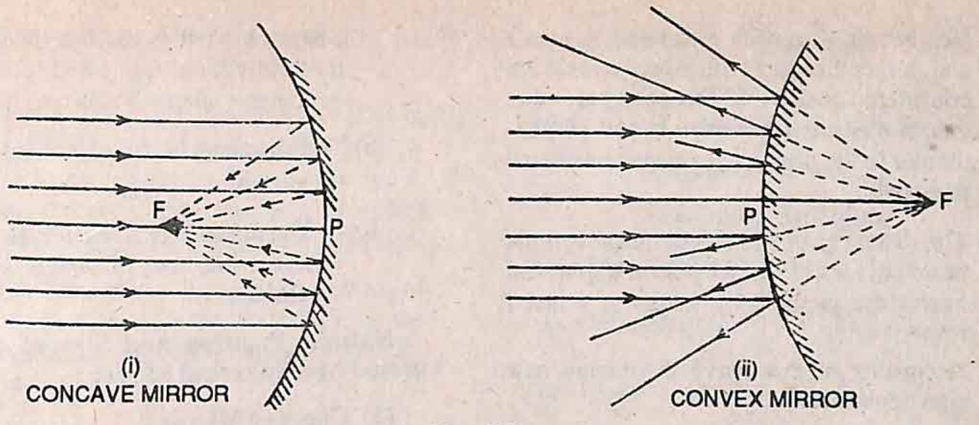
PRINCIPAL FOCUS

When a source of light is far from the mirror, and lies on the principal axis the rays of light from it would be almost parallel to the principal axis.

Let a beam of light parallel to the principal axis of a spherical mirror be incident on it near its pole. The reflected rays converge to or appear to diverge from, a point F (Fig. 7. 3) on the principal axis. This point is called **principal focus** of the spherical mirror. Thus the principal focus of a spherical mirror may be defined as follows :

"The principal focus of a spherical mirror may be defined as a point on its principal axis where a beam of light parallel to the principal axis converges to or appears to diverge from after reflection from the spherical mirror"

In the case of a concave mirror, the principal focus lies on its principal axis *in front of it* [Fig. 7.3(*i*)] and in the case of a convex mirror, the principal focus lies on its principal axis *behind it* [Fig 7.3(*ii*)].



(i) CONCAVE MIRROR

(ii) CONVEX MIRROR

Fig. 7.3

Focal length :

The distance of the principal focus from the vertex (or the pole) of the spherical mirror is called its focal length.

Image formation in spherical mirrors *(Graphical method) :–*

Let *PQ* be a small object placed on the principal axis of a spherical concave mirror M_1M_2 [Fig. 7.4(*i*)]. Since the object is an assembly of points, its image may be found as follows :

Consider a ray *PA* parallel to the principal axis. It strikes the spherical mirror at *A*. After suffering reflection, it passes through the focus *F*. Another ray *PC* passes through the centre of curvature of the concave mirror and as it strikes the mirror normally at *B* it retraces its steps along *BCP*. The reflected rays *AF* and *BCP* actually intersect each other at *P'* *which is the real* image of *P*. Another ray *PO* after reflection will travel along *OP'*. One may take another ray directed towards the focal point *F* which will be reflected *parallel* to the principal axis, again intersecting at *P*. Similarly, the image of any other point of the object can be determined. Draw a perpendicular from *P'* on the principal axis to cut it at *Q'*. It is clear from the Fig. 7.4(*i*) that *P'Q'* is the real inverted and diminished image of *PQ*, where *P'Q'* has been drawn perpendicular to the principal axis since *PQ* is also perpendicular to the principal axis.

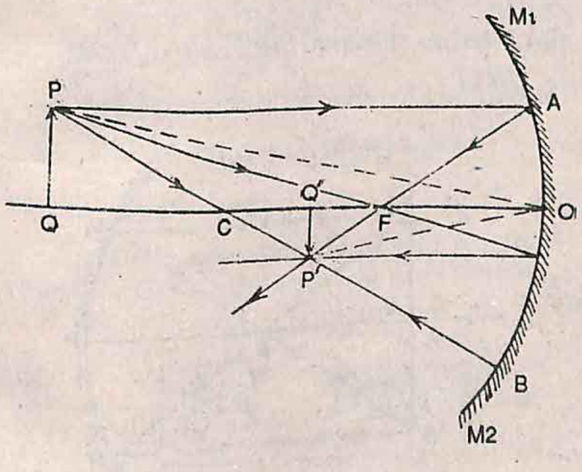


Fig. 7.4(i)

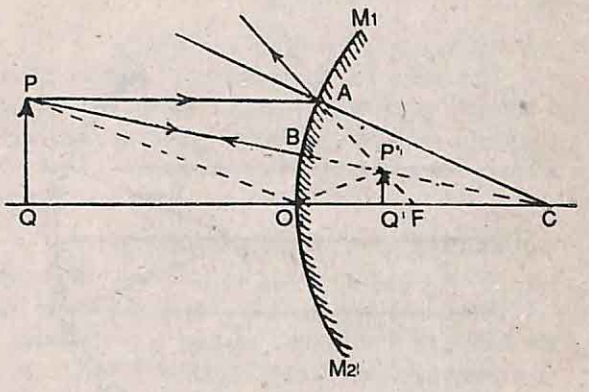


Fig. 7.4(ii)

Following the above construction, we find that *P' Q'* is the virtual, erect and diminished image of *PQ* formed by a convex mirror [Fig. 7.4 (*ii*)].

The graphical method consists of drawing the rays emanating from key points on the object and locating the points at which these rays are focussed by the mirror. For this purpose four kinds of rays are of particular importance :

1. A ray that is parallel to the principal axis and which is always reflected through the principal focus *F* of the mirror.

2. A ray that passes through the principal focus

(iv) Heights or distances measured *upwards* and perpendicular to the principal axis are considered **positive** whereas heights or distances measured *downwards* and perpendicular to the principal axis are considered **negative.**

(v) The distances of the object, image and the principal focus from the pole of a spherical mirror are denoted by letters u, v and f respectively.

According to the above mentioned new sign conventions :

(a) *Radius of curvature* and *focal length* of a **convex mirror** is taken as **positive** while the radius of curvature and focal length of a *concave mirror* is taken as **negative.**

(b) The distance of an *object* (u) is always **negative.**

(c) The distance of a *real image* (v) is **negative** while that of *virtual image* (v) is **positive.**

Nature, Position and Size of the Image Formed by a Spherical Mirror :

(1) Concave Mirror :

(i) *When the object lies at infinity*

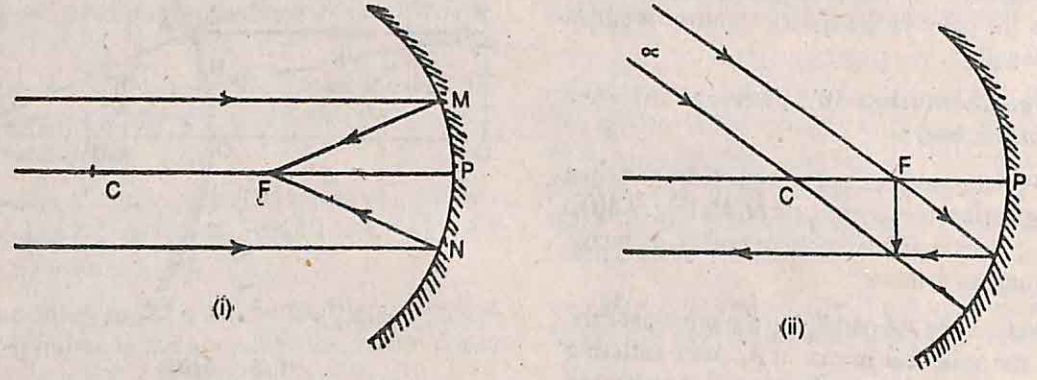


Fig. 7.6.

(ii) *When the object lies beyond the centre of curvature :*

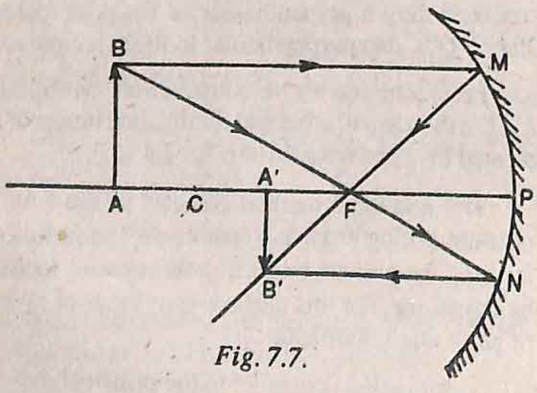


Fig. 7.7.

(iii). *When the object lies at the centre of curvature :*

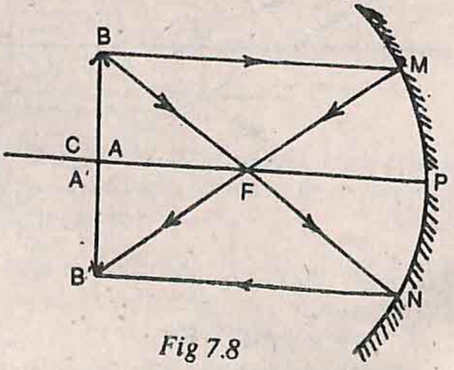


Fig 7.8

F first and which is then reflected parallel to the principal axis (the reverse of ray 1).

3. A ray which strikes the mirror at its vertex or pole (*i.e*, the point at which the principal axis intersects the mirror). Such a ray is always reflected in such a way that the angle of incidence with respect to the principal axis is equal to the angle of reflection.

4. The ray that passes through the centre of curvature and which is reflected back through the centre of curvature, since it strikes the mirror normally to its surface.

Spherical mirror formula :

A mathematical relation between the distance of the object from the pole, the distance of the image from the pole and the focal length of a spherical mirror is called the spherical mirror formula which is as follows :

$$\boxed{\frac{1}{u} + \frac{1}{v} = \frac{1}{f}}$$

where $u =$ distance of the object on the principal axis from the pole of the mirror

$v =$ distance of the image on the principal axis from the pole of the mirror

and $f =$ focal length of the spherical mirror.

This mirror formula is applicable for both concave and convex mirrors.

Relationship between focal length of a spherical mirror and its radius of curvature :

$\boxed{f = \frac{R}{2}}$ where R is the radius of curvature of a spherical mirror and f is the focal length.

Linear magnification :

The *linear magnification* may be defined as the ratio of the size of the image to the size of the object.

$$\boxed{m = \frac{I}{O}}$$

where $m =$ linear magnification

$I =$ size of the image

$O =$ size of the object.

For a *concave mirror*,

$$\text{magnification} = m = \frac{I}{O} = \frac{-v}{u} = \frac{f-v}{f} = \frac{f}{f-u}$$

For a *Convex mirror*,

$$\text{magnification} = m = \frac{I}{O} = \frac{-v}{u} = \frac{f-v}{f} = \frac{f}{f-u}$$

The magnitude of m can be greater or less than unity depends upon the values of u and v. If it is greater than unity *(i.e.,$m>1$)*, the image formed is enlarged otherwise it is diminished. If m is *positive*, the image formed is *erect*. If m is *negative* then the image is *inverted.*

In writing the above mentioned relations (*i.e.*, spherical mirror formula ; linear magnification and the relation between f and R), we use the **new sign Conventions** (cartesian convention) in which the pole P (or the vertex) of the spherical mirror is taken to be the origin of the rectangular coordinate system (Fig. 7.5). The new sign conventions are given below :

(i) The light rays will be taken to be travelling from left to right.

(ii) All distances are measured from the pole (or vertex) of a spherical mirror.

(iii) Distances measured in the *same* direction as that of the incident light are taken as *positive* and the distances measured *against* the direction of incident light are taken as *negative.*

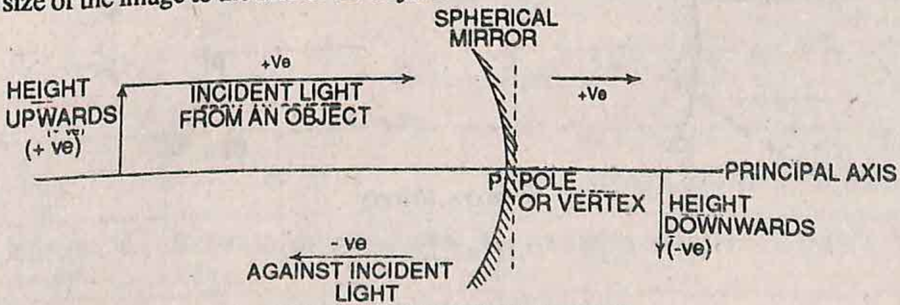


Fig. 7.5 NEW SIGN CONVENTIONS

(iv) *When the object lies inbetween the centre of curvature and the focus :*

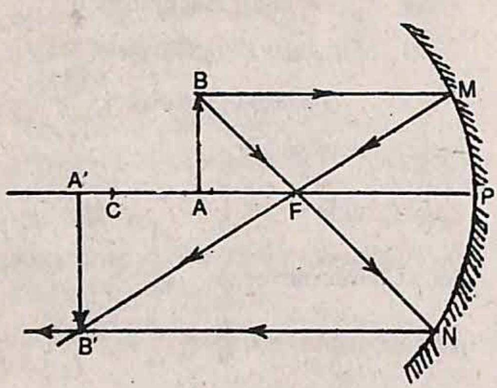


Fig. 7.9

(v) *When the object lies at the focus :*

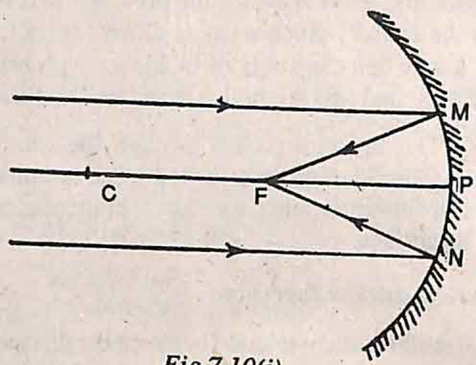


Fig 7.10(i)

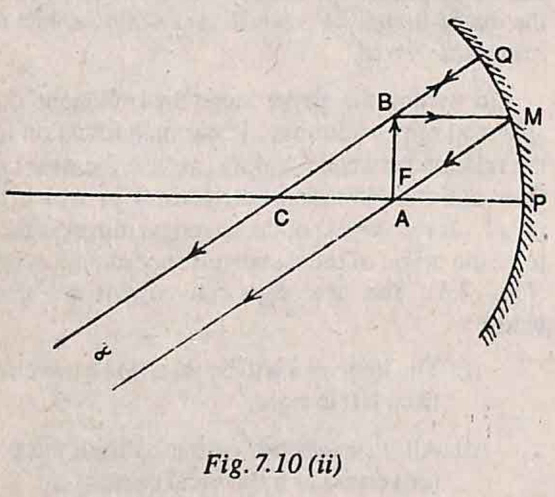


Fig. 7.10 (ii)

(vi) *When the object lies between the focus and the pole of the mirror :*

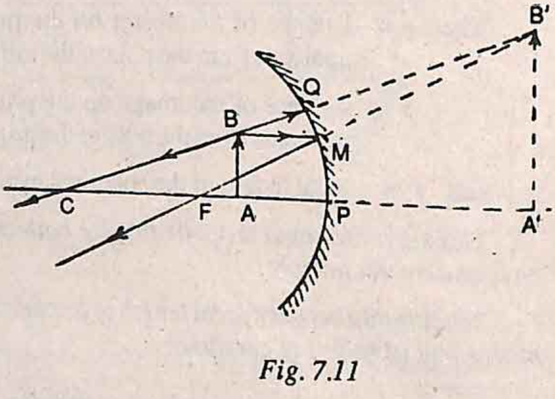
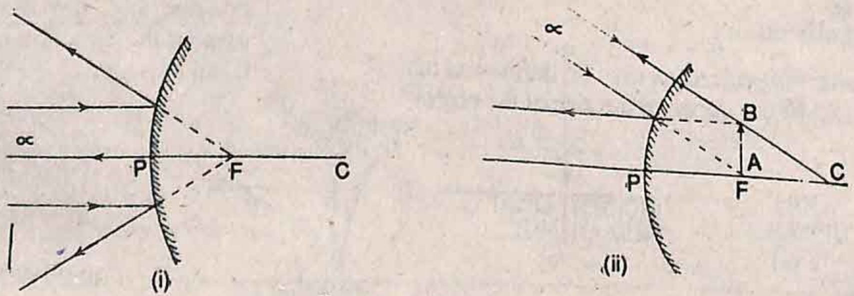


Fig. 7.11

(2) Convex Mirror

(i) *When the object lies at infinity :*



Convex Mirror

Fig 7.12

(ii) *When the object lies between infinity and the pole of the mirror :*

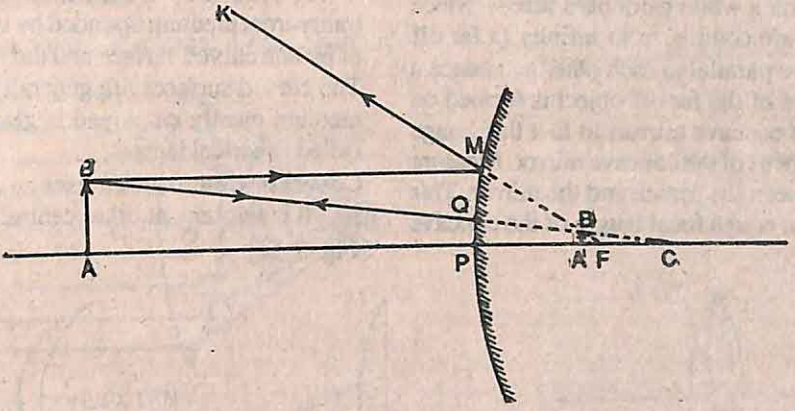


Fig 7.13

Concave Mirror

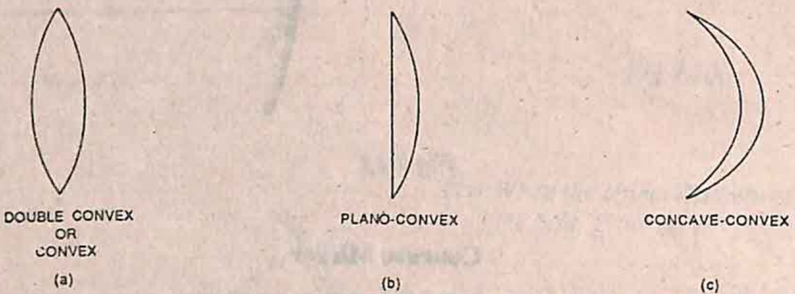
Position of the object	*Position of the image*	*Nature of the image*	*Size of the image*	*Ray Diagram*
At infinity	At Principal focus	Real and inverted	Extremely diminished	Fig 7.6
Beyond Centre of curvature	Between Principal focus and centre of curvature	Real and inverted	Smaller size than the object	Fig 7.7
At Centre of curvature	Also at centre of curvature	Real and inverted	Same size as the object	Fig 7.8
Between principal focus and centre of curvature	Beyond centre of curvature	Real and inverted	Greater in size than the object	Fig 7.9
At Principal focus	At infinity	Real and inverted	Highly magnified	Fig 7.10
Between pole and prinicapl focus	Behind the miror	Virtual and erect	Magnified	Fig 7.11
At the pole	Also at the pole	Virtual, erect, laterally inverted	Same size at the object	–

Convex Mirror

At infinity	*At focus*	*Virtual and erect*	*Extremely diminished*	**Fig 7.12**
Between infinity and pole of the mirror	Between pole and the focus	Always virtual and erect	Diminished	Fig 7.13

Focal lengths of Mirrors

Take a concave mirror and direct it towards a far off object such as the sun, a tree or a pole and focus the rays of light on a white cardboard screen. Since the rays of light are coming from infinity (a far off object) so they are parallel to each other and hence a diminished image of the far off object is formed on the screen by the concave mirror. In fact this image is formed at the focus of the concave mirror. Measure the distance between the screen and the mirror. This distance gives the *rough* focal length of the concave mirror.


DOUBLE CONVEX OR CONVEX (a)

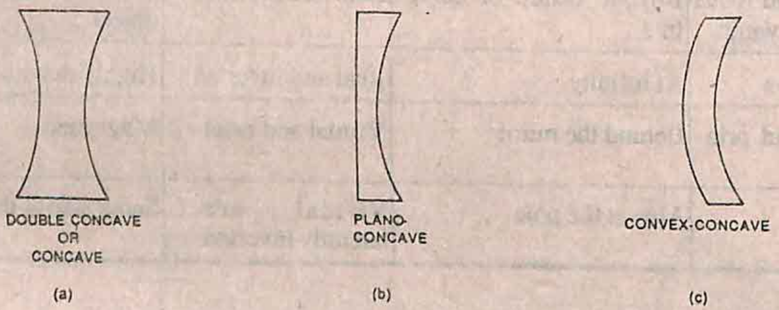
PLANO-CONVEX (b)

CONCAVE-CONVEX (c)

Fig 7.14

With a convex mirror, one gets a vertual image that cannot be obtained on a screen. We need a different method to measure its focal length.

7.3 REFRACTION THROUGH SPHERICAL LENSES : *(Revision work only)*


DOUBLE CONCAVE OR CONCAVE (a)

PLANO-CONCAVE (b)

CONVEX-CONCAVE (c)

Fig 7.15

In order to discuss the working of optical instruments *e.g.*, the camera the human eye, the telescope etc., it is necessary to revise the things learnt in earlier classes. A brief summary of a few terms related to spherical lenses and the formation of images by spherical lenses is given below :

Spherical lenses :

A lens may be defined as a portion of a transparent medium bounded by two curved surfaces or by one curved surface and the other plane surface. The curved surfaces are generally spherical and the medium mostly employed is glass. Such lenses are called spherical lenses.

Convex or Convergent lenses :

It is *thicker* at the centre than at the edges. (Fig. 7.14)

Concave or Divergent lenses :

It is *thinner* at the centre than at the edges. (See Fig. 7.15)

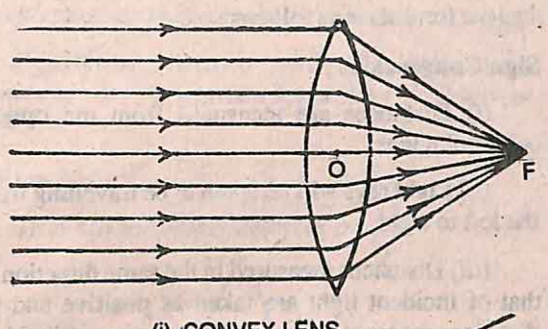
DEFINITIONS OF TERMS RELATING TO LENSES :

(*a*) **Principal Axis of a Lens.** *The straight line passing through the centres of curvature of the surfaces of the lens is called the* **principal axis of the lens.**

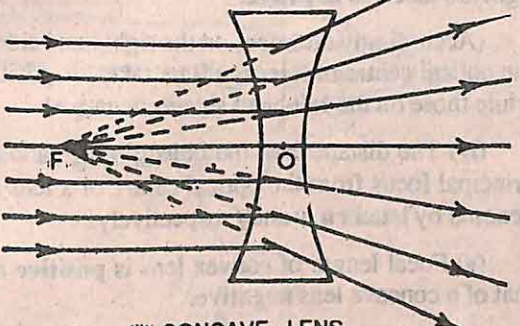
If one of the surfaces be plane as in the case of a plano-convex or plano-concave lens, the principal axis is normal to it and passes through the centre of curvature of the other surface.

(*b*) **Principal Section of a Lens.** *A section of the lens passing through its principal axis is called the* **principal section of the lens.**

(*c*) **Principal Focus of a Lens.** *When a beam of parallel rays of light falls on a lens in a direction parallel to its principal axis, the rays, after refraction through the lens, converge to or appear to diverge from a point on the principal axis. This point is called* **principal focus** *of the lens.*



(i) CONVEX LENS



(ii) CONCAVE LENS

Fig. 7.16

In the case of a convex lens, the beam of light parallel to its principal axis is mde to converge to a point F *on the other side* of the lens as shwon in Fig. 7.16 (i) whereas in the case of a concave lens, the beam of light parallel to its principal axis appears to diverge from a point *F on the same side of the lens* as the incident light as shown in Fig. 7.16 (ii).

(*d*) **Focal length of a Lens.** *The distance of the principal focus from the optical centre of the lens is called the* **focal length of a lens.**

(*e*) **Optical Centre of a Lens.** *The* **optical centre of a lens** *is the point on the principal axis, such that rays passing through it do not suffer any change in direction.* They may suffer lateral displacement. In other words, the optical centre of a lens is a peculiar fixed point such that a ray passing through it has its emergent path parallel to its incident path.

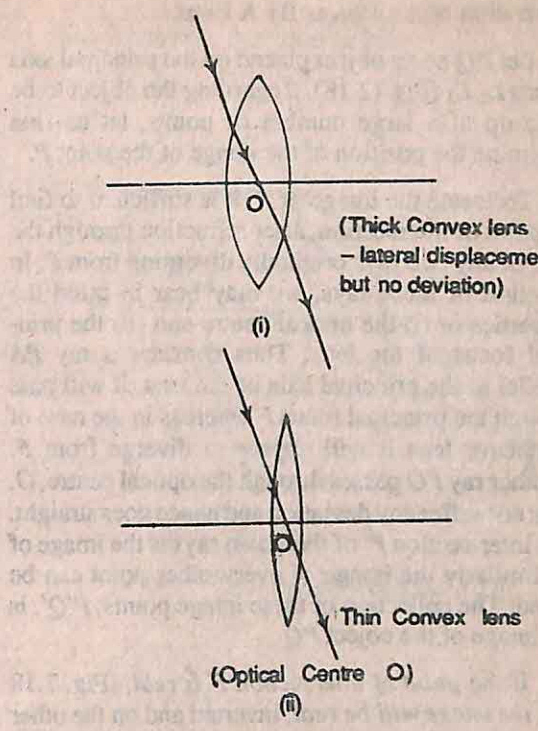


Fig. 7.17

(*f*) **Secondary axis of the lens :**

Evidently the pricipal axis defined in (a) above passes through the optical centre. Any straight line other than the principal axis passing through the optical centre is called the secondary axis of the lens.

Power of a lens :

It is the degree to which a lens converges or diverges the rays of light. It is measured as reciprocal of the focal length of a lens expressed in *metres*. Thus

$$\text{Power of a lens } (P) = \frac{1}{\text{focal length } (f) \text{ in metres}}$$

It is expressed in dioptres (D).

Suppose there is a convex lens whose focal length is 25 cm = 0·25m, its power (P) will be

$$P = \frac{1}{0{\cdot}25} = -4\text{D}$$

A concave lens of focal length $-20\ cm = -0.20\ m$ will have power (P) as

$$P = \frac{1}{-0.20} = -5\text{D}$$

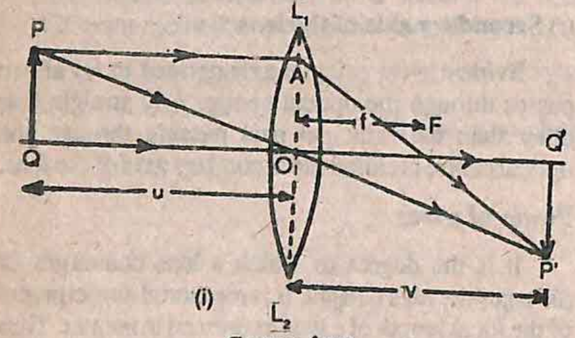
Formation of An Image By A Lens :

Let PQ be an object placed on the principal axis of lens $L_1 L_2$ (Fig 12.18). Regarding the object to be made up of a large number of points, let us first determine the position of the image of the point P.

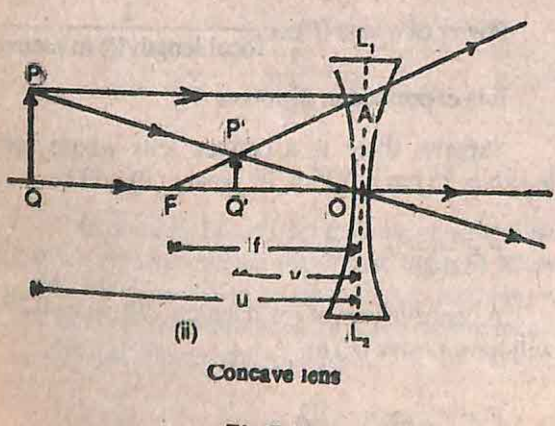
To locate the image of P, it is sufficient to find the point of intersection, after refraction through the lens, of any two rays originally diverging from P. In selection of these rays, we may bear in mind the properties of (i) the optical centre and (ii) the principal focus of the lens. Thus consider a ray PA parallel to the principal axis of the lens. It will pass through the principal focus F whereas in the case of a concave lens it will appear to diverge from F. Another ray PO passes through the optical centre, O, does not suffer any deviation and hence goes straight. The inter-section P' of these two rays is the image of P. Similarly the image of every other point can be found. The collection of these image points, $P'Q'$, is the image of the object PQ.

If the *point of intersection P' is real*, [Fig. 7.18 (i)], *the image will be real*, inverted and on the other side of the lens.

On the other hand, if the rays merely appear to intersect and do not actually intersect. *i.e., the inter-section is virtual* [Fig. 7.18 (ii)], *the image is virtual, erect* and on the same side of the lens on which the object lies.



Convex lens



Concave lens

Fig.7.18

LENS FORMULA :

The **new sign conventions** to be used in writing the lens formula is as follows :

Sign Conventions :

(*i*) Distances are measured from the optical centre of a lens.

(*ii*) Light rays will be taken to be travelling from the left to right.

(*iii*) Distances measured in the same direction as that of incident light are taken as **positive** and the distances measured against the direction of incident light are taken as **negative.**

(Accordingly distances on the right hand side of the optical centre of a lens will be taken as positive while those on the left-hand side as negative).

(*iv*) The distances of the object, image and the principal focus from the optical centre of a lens are denoted by letters u, v and f respectively.

(*v*) Focal length of convex lens is **positive** and that of a concave lens **negative.**

(vi) Heights measured above the principal axis are positive and those measured below the principal axis are negative.

Assumptions :

1. Thin lenses are used.
2. The incident rays of light are close to the principal axis of the lens.

Lens formula is a mathematical relation between the focal length (f) of the lens, the distance of the object (u) from the optical centre of the lens and the distance of the image (v) from the optical centre of the lens [See Fig 7.18). This relation is for convex as well as concave lenses.

$$\boxed{\frac{1}{v} - \frac{1}{u} = \frac{1}{f}}$$

Linear Magnification produced by a lens :

The linear magnification (m) produced by a lens is the ratio of the distance of the image (v) to that of the object (u) from the lens.

$m = \frac{I}{O} = \frac{v}{u}$ where I = Size of the image

and O = Size of the object

The ratio $\frac{v}{u}$ will be *positive* in the case of a *virtual image* and *negative* in the case of a real image.

Position, Nature And Magnification Produced By A Convex Lens And A Concave Lens :

Convex Lens :

(*i*) *When the object lies at infinity* :

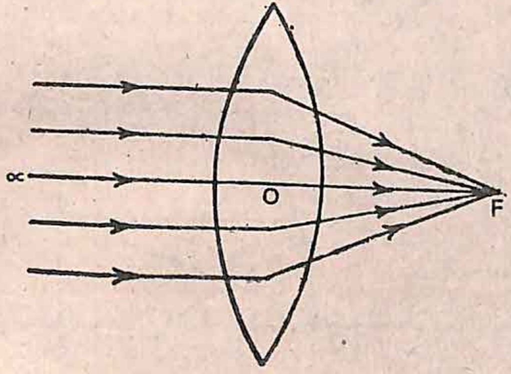


Fig 7.19 (a)

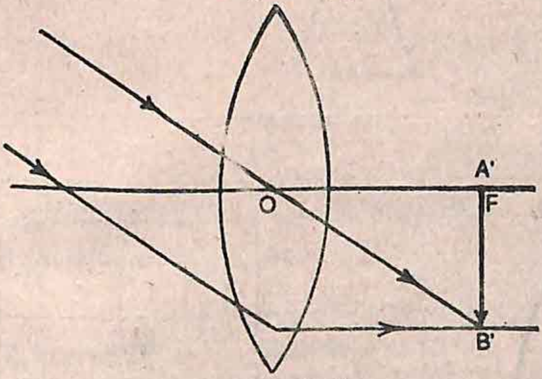


Fig 7.19 (b)

(*ii*) *When the object lies beyond 2F:*

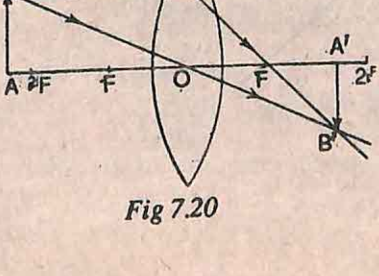


Fig 7.20

(*iii*) *When the object lies at 2F :*

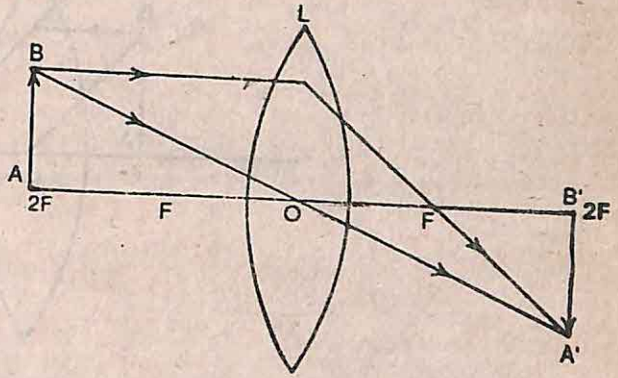


Fig 7.21

(*iv*) *When the object lies between Fard 2F:*

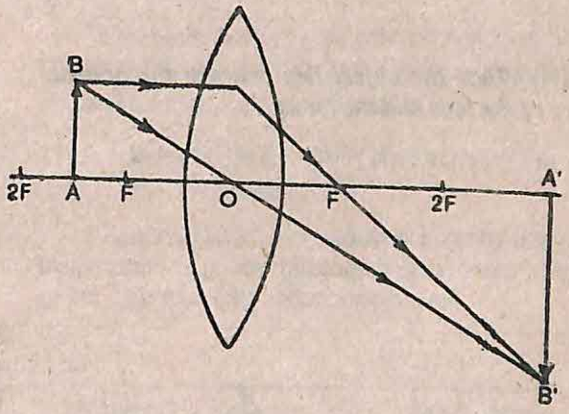


Fig 7.22

(*v*) *When the object lies of F;*

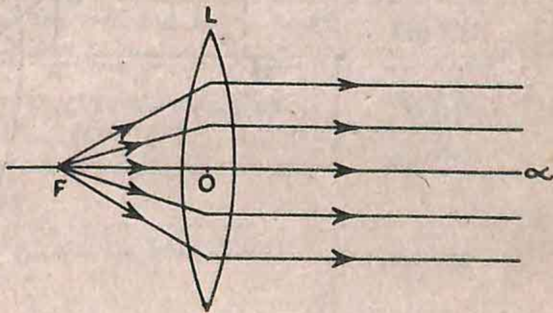


Fig 7.23 (a)

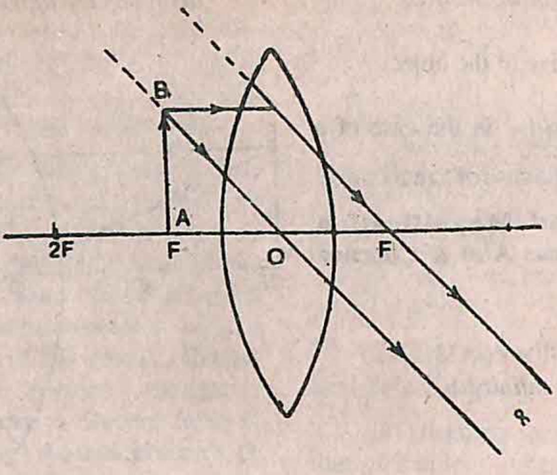


Fig. 7.23 (b)

(vi) When the object lies between the optical centre of the lens and the focus F :

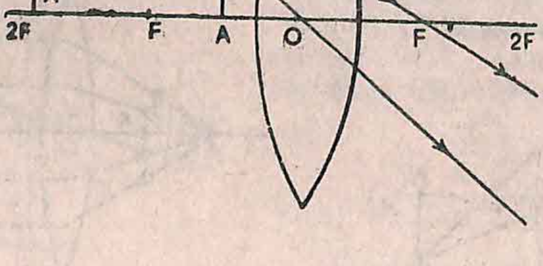


Fig. 7.24

Concave Lens :

(*i*) *When the object lies at infinity* :

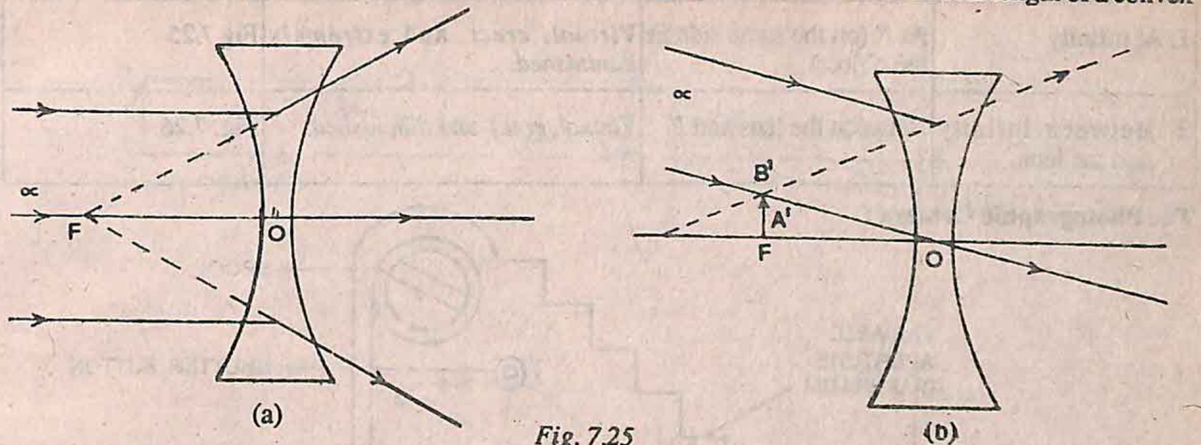


Fig. 7.25

(*ii*) *When the object lies between infinity and the lens :*

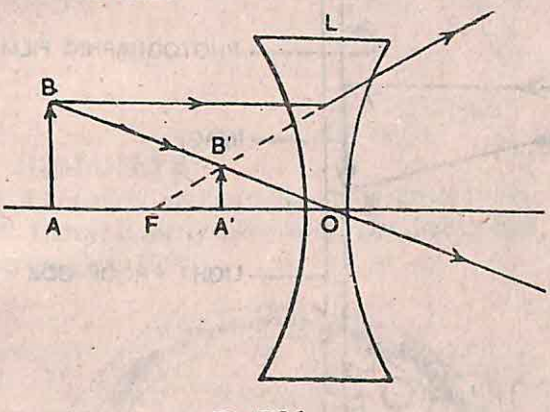


Fig 7.26

Focal lengths of lenses :

In order to determine the focal length of a convex lens, focus the image of a far off object such as a tree or a pole or the sun *sharply* on the screen using the canvex lens. The distance between the sharp image and the optical centre of the lens is the (**rough**) focal length of the convex lens.

With a concave lens one gets a virtual image that connot be obtained on a screen. We need a different method to measure its focal length.

7.4 SOME USES OF LENSES (OPTICAL INSTRUMENTS) :

Lenses are used very widely in almost all optical instruments *e.g.* the photographic camera ; spectacles ; microscopes and telescopes etc.

Convex Lens

Position of object	*Position of image*	*Nature and size*	*Ray Diagram*
1. At infinity	At *F*	*Real, inverted* and *extremely diminished.*	Fig 7.19
2. Beyond 2*F*	Between *F* and 2*F*	*Real, inverted* and *diminished.*	Fig 7.20
3. At 2*F*	Also at 2*F*	*Real, inverted* and *same size as the object.*	Fig 7.21
4. Between *F* and 2*F*	Beyond 2*F*	*Real, inverted* and *magnified.*	Fig 7.22
5. At *F*	At infinity	*Real, inverted* and *highly magnified.*	Fig 7,23
6. Within F	On the same side as the object.	*Virtual, erect* and *magnified.*	Fig 7 24

Concave Lens

Position of object	*Position of Image*	*Nature and size*	*Ray Diagram*
1. At infinity	At *F* (on the same side as the object)	*Virtual, erect* and *extremely diminished.*	Fig 7.25
2. Between infinity and the lens.	Between the lens and *F*	*Virtual, erect* and *diminished.*	Fig. 7.26

The Photographic Camera :

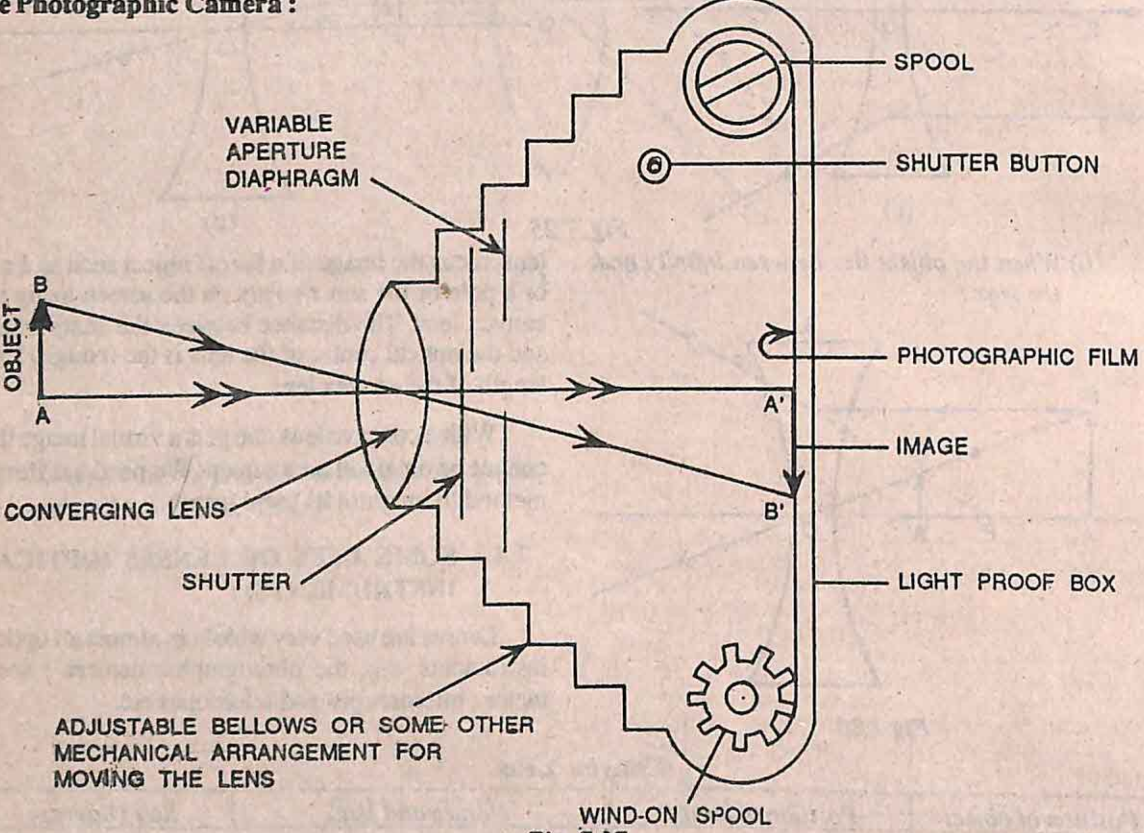


Fig. 7.27

The photographic camera is made from a converging lens fitted in one face of a light-proof box which can be moved towards or away from a light sensitive photographic film with the help of a bellow or some other mechanical arrangement [Fig 7.27]. The lens is positioned so that a sharp image is produced on the film, depending on the distance of the object from the lens. A variable speed shutter behind the lens allows the light to enter the camera for the amount of time needed to expose the film correctly. If a fast moving object is to be photographed then the fastest shutter speed should be used to prevent the photograph from being blurred.

Behind the shutter there is a variable diameter aperture or stop which controls the amount of light which can pass through the lens and on to the film. The aperture also controls the depth of field which can be focussed by the camera. A narrow aperture gives a large depth of field, while a wide aperture gives a small depth of field around a given object. Objects outside this narrow range are out of focus. The converging lens is positioned so that a real, inverted image is formed on the film. To take distant objects the lens is moved closer to the film and for near objects the lens is moved away from the film [Fig 12.28 (a) and (b)].

When the film is developed it can be printed on paper using an enlarger or on a transparent material to produce a slide.

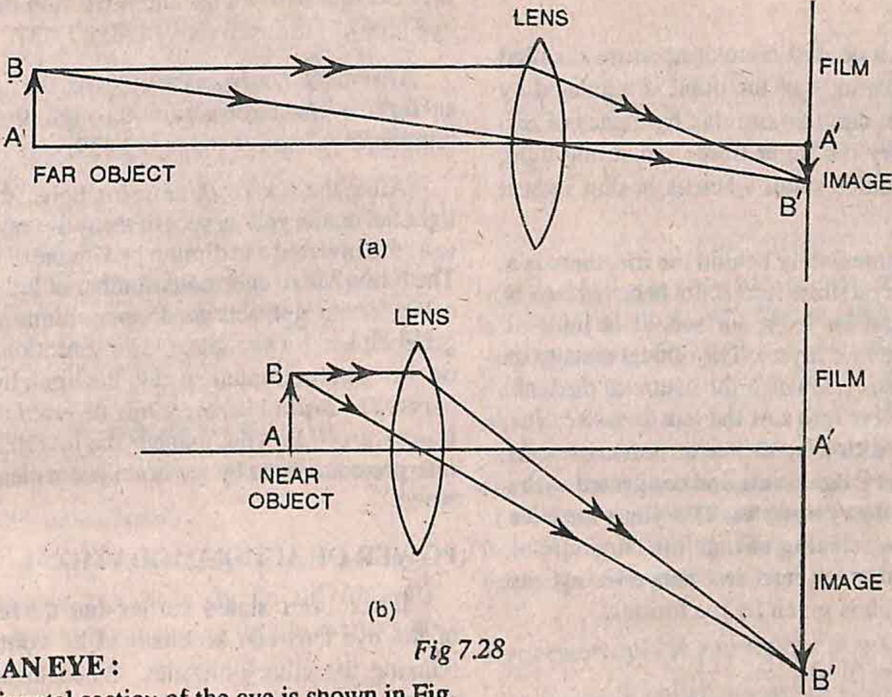


Fig 7.28

HUMAN EYE :

A horizontal section of the eye is shown in Fig. 7.29. The eye is nearly spherical in shape. Its essential parts are given below :

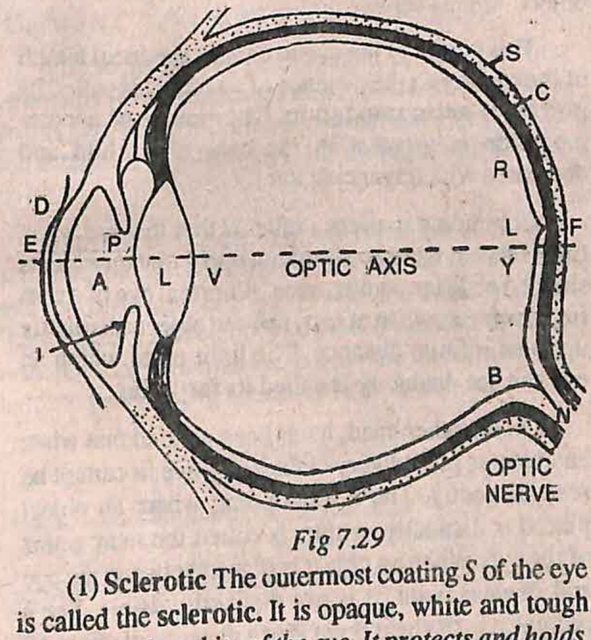


Fig 7.29

(1) **Sclerotic** The outermost coating *S* of the eye is called the **sclerotic**. It is opaque, white and tough and forms the *white of the eye. It protects and holds the eye-ball. The front portion D*, of the opaque scleretic is transparent and more convex than the remaining portion. This transparent portion which bulges out is called the **cornea**. Its refractive index is 1·337.

(2) **Choroid**. The second coat, *C*, inside the sclerotic is called **choroid**. It is a black membrane which forms the black of the eye and darkens the interior of the eye.

(3) **Retina**. The third coat ; *R* which forms the innermost coating of the eye is called the **retina**. It is a semi-transparent, delicate membrane profusely supplied with nerve fibres and blood vessels. It is sensitive to light and serves the purpose of a sensitive screen for the reception of the images formed by the optical system of the eye. The retina sends electrical signals to the brain through the optic nerve so that we perceive images.

The retina possesses the following two important points :

(i) **The yellow spot**, y, is situated at the centre of the retina. It is a slightly raised spot with a minute depression L at its summit. It is yellow in colour and most sensitive to light. The central region of the yellow spot is called the **fovea centralis**.

(ii) **The blind spot**, *B* where the optic nerve *N* enters the eye is also a raised spot but absolutely insensitive to light. It is not covered by the choroid and the retina.

(4) **Iris.** Behind the cornea there is an opaque diaphragm *I*, called the **Iris**. Its colour is different in different persons and also in persons of different countries.

The iris has a central circular aperture *P* called the **pupil**. The diameter of the pupil is regulated by the iris which can contract or relax by means of two sets of involuntary muscular fibres. In strong light, the aperture becomes small whereas in dim light it becomes large.

(5) **Lens.** Immediately behind the iris, there is a double convex crystalline lens *L*. Its back surface is more convex than its front surface. It is built of transparent concentric layers. The optical density of these layers increases *towards* the centre of the lens. The mean refractive index of the lens is 1.437. The lens is held in position by means of non-contracile tissues **suspensary ligaments** and connected to the sclerotic by the **ciliary muscles**. The ciliary muscles by contracting or relaxing change the curvature of the surfaces of the eye lens and hence change its focal length which is given by the formula.

$$\frac{1}{f} = (\mu -) \left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

where f = focal length of the lens
μ = Mean refractive index of the material of the lens.
R_1, R_2 = Radii of curvature of the two sur faces of the lens.

(6) **Optic Axis.** The line, *PY*, passing through the centre of the cornea and that of the lens is called the **optic axis** of the eye.

(7) **Anterior Chamber and aqueous humour.** The space *A* between the lens *L* and the cornea *D* is called the **anterior chamber**. It is filled with a watery liquid containing a little common salt. This liquid is called the **aqueous humour**. Its refractive index is 1·337.

(8) **Posterior chamber and vitreous humour.** The space *V* between the retina *R* and the lens *L* is called the **posterior chamber**. It is filled with a viscous transparent liquid of refractive index 1·437. This liquid is called the vitreous humour.

Action of the Eye. As the cornea and aqueous humour have the same refractive index (1·337), they may be regarded to form a single homogeneous medium. Thus, on entering the eye rays of light from an object suffer *first* refraction through the cornea and the aqueous humour.

On emergence from the aqueous humour, the rays of light suffer a second refraction through the eye lens of mean refractive index 1.437.

On emergence from the eye lens, the rays of light suffer the *third* refraction through the vitreous humour of refractive index is 1·437.

After the above *three* refractions, the rays of light fall on the yellow spot of the retina and give rise to a real, inverted and diminished image of the object. The retina has an enormous number of light sensitive cells. These get activated upon illumination and generate electrical signals. The sensation produced on the eye is communicated to the brain by the optic nerve. *The brain interprets this inverted image as if it were erect.* In what manner the inverted image is interpreted as erect by the brain is not clearly understood.

POWER OF ACCOMMODATION :

It has been stated earlier that the focal length of the eye lens can be changed by contracting or relaxing the ciliary muscles. When these muscles contract, they thicken the lens or make its surfaces more convex thereby decreasing its focal length. This enables an observer to focus accurately the near object.

This power of the eye to change the focal length of the eye to suit the distance of an object is called its **power of accommodation**. The power of accommodation is greatest in the case of a child and decreases with advancing age.

Common experience tells us that the eye when fully relaxed can see simultaneously distant objects situated at different distances. A normal eye of a care free observer, when at rest, can see objects distinctly up to an infinite distance. The limit up to which an eye can see distinctly is called its **far point**.

On the other hand, it has been noticed that when an object is placed very close to the eye, it cannot be seen distinctly. The nearest point, where an object placed is distinctly visible, is called the **near point** of the eye. When an object is placed between the eye and its near point, it is not distinctly visible. For a normal eye, the near point is at a distance of about 15 cm.

The distance between the near point and the far point is called the **range of vision**.

Thus, notice that due to the power of accommodation an eye can see distinctly objects placed between its far point and its near point. In other words its range of vision is infinite. Within this range of vision, there is one point where objects placed are mostly distinctly visible. The distance between this point and the eye is called the **distance of distinct vision.** For a normal eye the distance of distinct vision is *25 cm.*

DEFECTS OF THE EYE :

Due to certain causes, an eye cannot accommodate itself to various distances. The vision is then called defective. The **chief defects** of the eye are given below :

(1) Myopia (short-sightedness).

(2) Hypermetropia (long-sightedness).

Myopia (Short sightedness)

A man suffering from **myopia** can see near objects but cannot see distinctly far off (distant) objects as his eye **ball** is *too long* for his eye lens or the eye lens becomes *too convergent.*

Due to the above defects, the image of an object situated beyond a certain distance, called **his far point,** is formed *in front of retina* and consequently is either not visible at all or indistinctly visible.

The myopia may be corrected by using a **concave lens** *(divergent lens)* of a suitable focal length so that parallel rays coming from distant objects after refraction through it appear to diverge from his far point.

Suppose the far point of a myopic eye is *P*. Rays starting from an object placed at *P* are focused by the eye lens on the retina and give rise to a distinct vision. Rays starting from an object placed *within P* and his near point *N'* are made to fall on the retina with the help of power of accommodation. It may be noted here that *his near point N'* is closer to the eye than the normal near point *N'*. On the other hand, the rays starting from an object placed beyond *P* upto infinity are brought to focus in *front* of the retina [Fig. (7.30 (a)]. Consequently it is not distinctly visible. On placing **concave lens of focal length equal to the distance between the eye and his far point in front of the eye,** the parallel rays will appear to diverge from *P* [Fig. 7.30 (b)]. They will be focussed on the retina and thus give rise to a distinct vision.

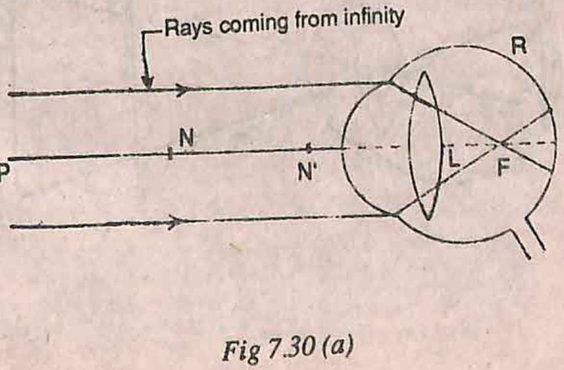


Fig 7.30 (a)

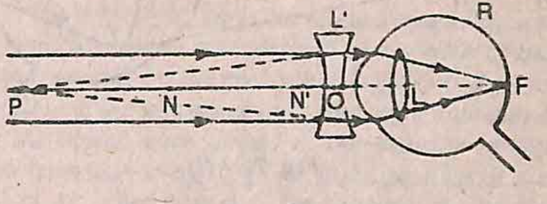


Fig 7.30 (b)

Hypermetropia (Long sightedness).

A man suffering from hypermetropia of long-sightedness can see distinctly distant objects but cannot see distinctly near objects lying within a certain point as his eyeball has become *too small* or his eye lens has become *less convergent.*

Due to the above defect, the image of a near object situated within a certain distance called **his distance of distinct vision,** is formed behind the retina and consequently is either not visible at all or indistinctly visible.

The hypermetropia may be corrected by using a **convex lens** (convergent lens) of a suitable focal length so that rays coming from an object placed at *the distance of normal distinct vision* (25 cm) after refraction through it appear to diverge from a point the *distnace of distinct vision* of the defected eye.

Suppose a hypermetropic eye can see beyond *N'* upto infinity but objects lying between *N' and N are not distinctly seen* [Fig. 7.31 (i)] where *N* is the point at a distance of the **normal distinct vision** from the eye. Evidently *N'* is farther from the eye than *N'*. The rays starting from an object placed at *N'* are focussed by the eye lens on the retina and give rise to a distinct vision. Rays starting from an object lying beyond *N'* upto infinity are focussed on the retina

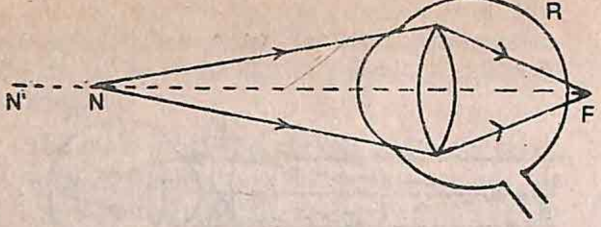


Fig. 7.31 (i)

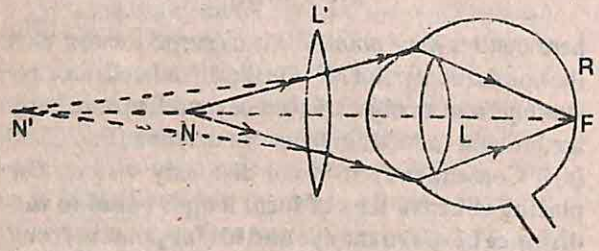


Fig. 7.31 (ii)

by the eye lens by means of the power of accommodation. But the rays starting from an object placed between N' and N or at N are brought to focus *behind* the retina Consequently, it is not distinctly visible. On placing a convex lens of such a focal length, a virtual image of an object placed at N is formed at N' [Fig. 7.31 (ii)] so that rays appearing to come from his near point N' are focussed on the retina and hence the image is clearly visible.

COMPARSION BETWEEN A PHOTOGRAPHIC CAMERA AND THE EYE :

Camera	*Eye*
1. The light tight box to prevent the extraneous light from outside.	The opaque sclerotic to prevent the extraneous light.
2. The box is darkened from inside to stop reflection within the camera.	The sclerotic is lined with dark choroid, to stop reflection within the eye.
3. A converging lens system free from spherical and chromatic aberrations and other defects to produce a real, inverted and diminished image on the sensitive film.	The cornea, the aqueous humour, the crystalline lens and the vitreous humour constitute the lens system to produce a real, inverted and diminished image on the retina of the eye
4. The sensitive film after *developing* and *fixing* retains a permanent image.	The sensation on the retina is communicated to the brain by the optic nerves of the eye. The impression lasts for a moment.
5. The adjustable diaphragm regulates the size of the aperture and hence the quantity of light admitted into the camera.	The iris regulates the size of the pupil and hence the quantity of light admitted into the eye.
6. The shutter regulates the times of exposure.	The eye-lid can cut off or admit light for any period.
7. The focussing of objects at different distances is done by changing the distance between the lens and the s~~e~~creen which is subsequently replaced by a sensitive film.	The focussing of objects at different distances is done by the power of accommmodation of the eye.

ANGULAR VISION :

Consider an object AB placed in front of the eye at a certain distance (Fig. 7.32). The image formed on the retina is ab. If the same object is brought nearer to the eye and placed in the position $A'B'$, the image formed is $a'b'$. Clearly, $a'b'$ is greater than $a\,b$. *Thus* to the eye the object in the position AB appears smaller than when it is placed in the position $A'B'$. It shows that the apparent size of an object depends upon its distance from the eye.

From the Fig. 7.32, it is clear that the angle A'OB' subtended at the eye by the object in the

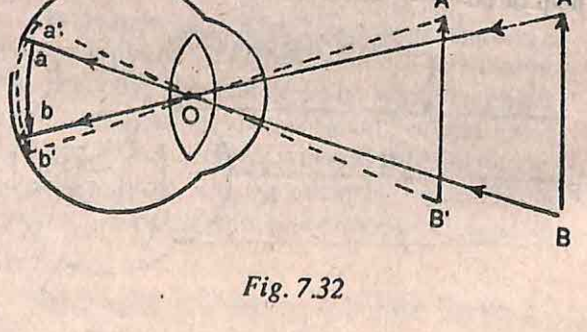


Fig. 7.32

position $A'B'$ is greater than the angle AOB subtended by it in the position AB. This shows that *the eye estimates the angle subtended by an object on it and not the linear size of the object.*

The angle subtended at the eye by the object or image is called the **visual angle.**

The railway lines appear to converge to a point though actually they are parallel to each other. Similarly, the moon appears to be as large as the sun though the latter is known to be much greater in size than the former.

MAGNIFYING GLASS OR SIMPLE MICROSCOPE.

To see the fine details of a small object, we have to bring it as near the eye as possible so that the angle subtended by it at the eye may increase and so appear to be large. But there is a limit upto which it can be brought closer to the eye. If it is placed within the distance of distinct vision, it is not distinctly visible. Consequently to study a minute object we make use of magnifying glass or simple microscope which produces a virtual image at the distance of distinct vision of an object placed close to the eye.

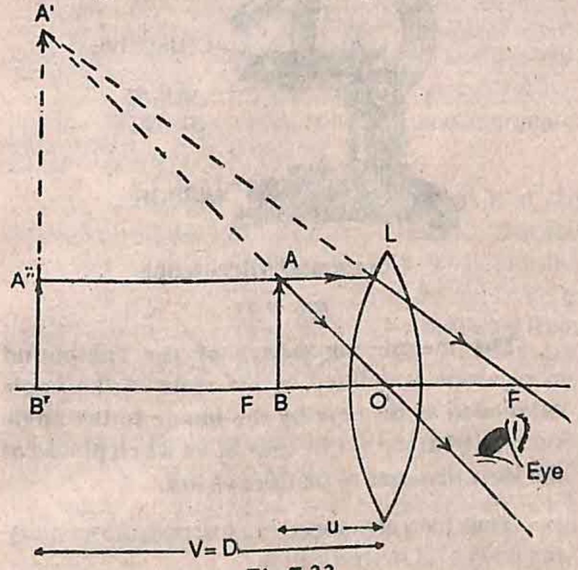


Fig 7.33

A magnifying glass or a simple microscope is an ordinary convex lens of short focal length. When an object AB is placed within the principal focus of the convex lens L (Fig 7.33), the eye E placed on its other side sees the virtual image $A'B'$. The distance of the object between, F, the focus, and O, the optical centre of the lens L may be so adjusted that the virtual image $A'B'$ is formed at the distance of distinct vision, D (25 cm). The image will be then distinctly visible

*Angular Magnification or Magnifying Power of a simple Microscope

The magnifying power or angular magnification of a microscope may be defined *as the ratio of the angle subtended at the eye by the image formed at the distance of the distinct vision to the angle subtended by the object when placed at the distance of the distinct vision.* Thus, if $A''B'$ is the position of the object AB when placed at the distance of distinct vision and the eye E is very close to the lens L, we have

Magnifying power of the simple microscope or magnifying glass

$$= \frac{\text{Angle subtended at the eye by the } \textit{image formed} \text{ at the distance of the distinct vision}}{\text{Angle subtended at the eye by the } \textit{object placed} \text{ at the distance of the object vision}}$$

$$= \frac{\angle A'OB'}{\angle A''OB'} \left[\begin{array}{r} \text{For the sake of clarity} \\ A''O \text{ has not been joined} \end{array} \right]$$

$$(7) = \frac{\angle AoB}{\angle AoB} \approx \frac{\tan\angle AoB}{\tan\angle A''oB} \quad \text{(when } \theta \text{ is small and in radian's } \theta \approx \tan\theta\text{)}$$

$$= \frac{AB / oB}{A''B' / OB'} = \frac{AB}{OB} = \frac{OB'}{A'B'} = \frac{OB'}{OB}$$

$\because AB = A''B'$) or $m = D / u$

where $D = OB' =$ Distance of the distinct vision from the lens or eye and

$u = OB =$ Distance of the object from the lens or eye

$m =$ Magnifying power of the convex lens or simple microscope.

Since the image $A''B'$ formed at the distance D is virtual, therefore $v = -D$. According to the lens formula

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

$$\therefore \quad \frac{1}{u} = \frac{1}{v} - \frac{1}{f}$$

and $$m = \frac{v}{u} = 1 - \frac{v}{f} = 1 + \frac{D}{f}$$

---

* For further knowledge only. Only the formula $m = 1 + \frac{D}{f} = 1 + \frac{25}{f}$ is to be remembered.

Where f is the focal length of the convex lens

or $$m = \frac{D}{u} = (1 + \frac{D}{f}) = 1 + \frac{25}{f} \quad ...(2)$$

or Magnifying power of the simple microscope (convex lens)

$$= 1 + \frac{\text{Distance of distinct vision}}{\text{Focal length of the convex lens}}$$

The above relation shows that a convex lens of short focal length has large magnifying power.

A simple microscope ordinarily has a magnifying power 20. If greater magnifying power is required, we use a compound microscope.

COMPOUND MICROSCOPE :

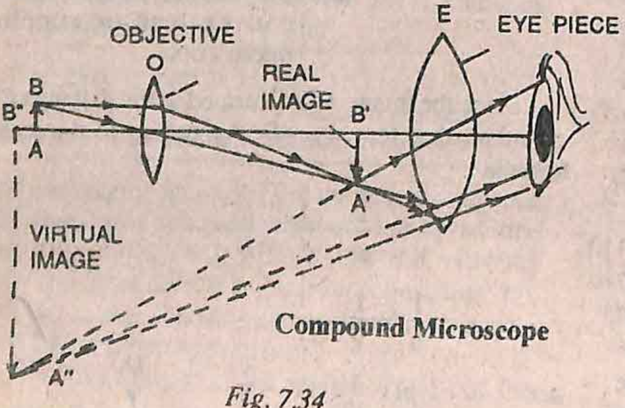
A compound microscope is an optical instrument which is used to magnify very small objects like blood cells, bacteria etc., which otherwise cannot be seen clearly with the naked eye.

The essential parts of a compound microscope are two *convex lenses of short focal length.

(1) The **object glass** or objective,

(2) The **eye-piece** or lens.

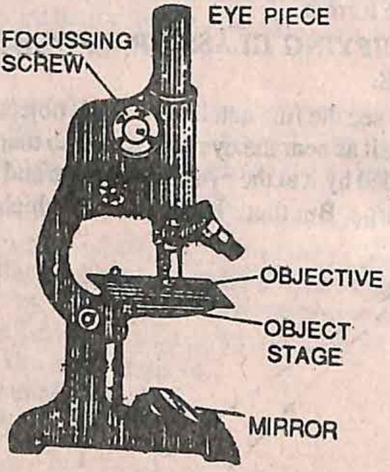
The distance between the object and the objective is **little greater** than the focal length of the objective. Consequently a real, inverted, magnified image is produced on the other side of the lens. In Fig. 7.34, AB is the object, A′B′ is the real, magnified, inverted image formed by the objective O. This real image is then viewed through the eye lens which acts in exactly the same way as a magnifying glass.



Compound Microscope

Fig. 7.34

The distance between the real image and the eye-lens is less than the focal length of the lens consequently a magnified virtual image is produced. The lens is adjusted so that this vritual image is formed *at the least distance of distinct vision* usually taken as 25 cm from the eye $A'B'$ is the real image formed by the objective, $A''B''$ is the virtual image formed by the eye-piece E.



Compound Microscope

Fig. 7.35

The magnifying power of the compound microscope is defined as the ratio of the angle subtended at the eye by the image to the angle subtended at the eye by the object when placed at the least distance of distinct vision.

Thus for a compound microscope, the magnifying power of magnification is

$$m = \frac{A''B''}{AB}$$

or $$m = \frac{A''B''}{A'B'} \cdot \frac{A'B'}{AB}$$

$$= m_e \times m_o \approx \frac{D \times L}{F \times f}$$

where m^e is the magnification produced by eye piece and m_o is the magnification produced by the objective, D = 25 cm is the distance of distinct vision; L is the length of the microscope tube. F and f the focal lengths of the objective and the eye piece respectively.

---

* The lenses used in practice are combination of lenses in order to minimise spherical and chromatic oberrations.

The magnification produced by a good compound microscope is upto 5000 or more. The object must be strongly illuminated if a bright image is to be seen.

ASTRONOMICAL TELESCOPE :

It is an optical instrument used to see heavenly bodies.

The astronomical telescope consists of two convex lenses :

(i) The objective O of *very long* focal length and wide aperture, and

(ii) The eye-piece E of *very short focal* length and small aperture.

The eye-piece E is fixed in a brass tube which can slide in the second tube at the other end of which the objective O is fixed. The objective and the eye-piece are not single lenses but convergent combination of lenses free from spherical and chromatic aberrations and other defects.

Let XY be the common principal axis of the objective O and the eye-piece E. Imagine that the objective O is facing a distant object. Let it be situated at right angles of XY produced. Since the object is far off we may suppose that a parallel beam started from its top. This parallel beam is inclined to the XY at a small angle . (Fig 7.36).

If the beam had been parallel to XY, after refraction through the objective O, it would have been brought to its principal focus F lying on its principal axis XY. Since it is inclined to XY, it is brought to focus at I which lies on the *secondary axis* or the focal plane. Thus, I is the image of the top of the object. Draw IF perpendicular to XY. Then IF is the image of the distant object formed by the objective O. The image IF is real, inverted and diminished.

Suppose IF is at the principal focus of the eye-piece E. A ray IE passing through its optical centre will go straight along IEC. Other rays from the image I after refraction through the eye-piece E will be formed at infinity. This adjustment of the telescope is called **normal adjustment**. This is shown in Fig. 7.36.

If the image IF, lies between the focus F_e and the optical centre of the eye-piece E, the final image $A'B'$ will be virtual and magnified but inverted in the original sense of the object. The distance of the eye-piece E from IF can be so adjusted that the image $A'B'$ is formed at distance of distinct vision. This is shown in Fig. 7.37.

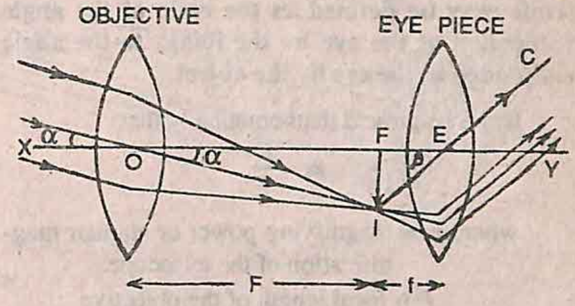


Fig. 7.36

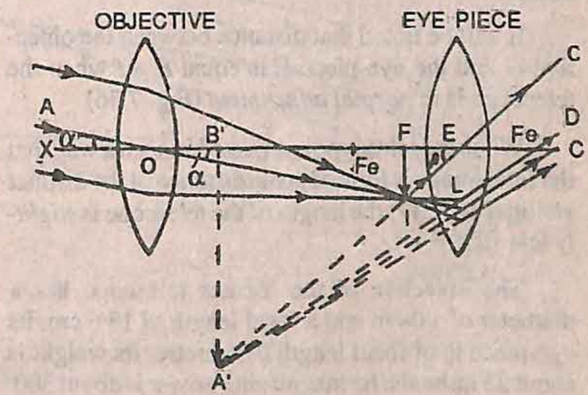


Fig. 7.37

In order to trace the course of rays forming the final image $A'B'$ we need to take two rays. The ray IL travelling parallel to the principal axis XY, after refraction at the eye-piece E passes through its principal focus F_e. Another ray IE passing through its optical centre goes straight along IEC. These rays when produced backwards appear to meet at A' which is, therefore, the virtual image of I. The other rays forming the image I after refraction at the eye-piece also appear to diverge from A'. Draw $A'B'$ perpendicular to XY. Then $A'B'$ is the final image. It is *virtual*, erect in the sense of IF but *inverted* in the sense of the distant object and magnified.

Since the final image formed by it is inverted, the telescope described above is used for seeing the *celestial objects* only.

Magnifying power of the Astronomical Telescope may be defined as the ratio of the angle subtended at the eye by the image to the angle subtended at the eye by the object.

It can be proved mathematically that

$$m=\frac{F}{f}$$

where m = magnifying power or angular magnification of the telescope.

F = focal length of the objective

and f = focal length of the eyepiece.

For high angular magnification or magnifying power, it is clear from the above expression that F, the focal length of the objective should be large whereas the focal length f of the eye-piece should be small.

It will be noted that distance between the objective O and the eye-piece E is equal $F + f$ when the telescope is in *normal adjustment* (Fig. 7.36).

When the telescope is adjusted in such a way that the final image is formed at the distance of the distinct vision (Fig. 7.37) the length of the telescope is *slightly* less than F + f.

The objective of the Yerkes telescope has a diameter of 1·08 m and a focal length of 18·6 cm. Its eye-piece is of focal length 0·64 metre. Its weight is about 23 quintals. Its magnifying power is about 300.

7.5 DISPERSION OF LIGHT BY A PRISM

(The splitting of white light) :

Take a prism or a lens ; hold it close to your eye and use it to view objects in the room. You will find that the edges of the various objects appear to be of several colours. This will be seen most easily through a glass prism.

Sir Isaac Newton was the first to investigate the effect. Sometime in 1666 Newton darkened his room at Trinity College, Cambridge, and allowed a beam of sunlight to pass through a small, circular hole in the shutter of his room, forming a white, circular patch on the opposite wall. He then placed a triangular glass prism in the path of the beam of light. He found, firstly, that the white spot on the wall had changed its position and, secondly, the light was no longer white but coloured.

Newton examined the colours very carefully and could make out the seven colours of the rainbow:*red, orange, yellow, green, blue, indigo and violet*, in that order. But there was no clear distinct line between one colour and the other. **This coloured band he called a spectrum.**

Now try to produce a spectrum yourself.

Experiment. *To produce a spectrum of white light.*

Requirements. The ray apparatus producing white light, triangular glass prism, white screen.

Procedure. Let a narrow beam of white light from the ray apparatus strike the prism and allow the beam that comes out of the prism to strike the white screen. Examine what appears on the screen (Fig. 7.38).

On the screen, instead of white light which you would see at *A* in the absence of the prism, you should now see coloured light at *B*. If you look carefully you will be able to make out the seven colours of the rainbow in the order given above. You will not be able to see each colour standing separately, as they all run into one another.

Explanation. The prism is able to split white light into its seven colours because the glass can bend the different colours by different amounts so that on coming out of the prism they come out separately at different angles (Fig. 7.38). *The colour violet is bent the most, while the red is bent least.*

This splitting of white light into various colours is known as dispersion and the colours obtained on the screen form the spectrum of white light.

Pure spectrum. It has been said above that the spectrum consists of colours which run into one another, *i.e.*, they overlap. The spectrum as formed above is therefore not pure. By combining the prism with two lenses, it is possible to produce a pure spectrum in which each colour is distinct from the other. Fig.7.39 shows how this is done. The slit through which the light originates must be narrow, and the prism must be placed in a special position. You will learn more about this in the higher classes.

Newton wanted to know if each colour could be split further, and so he made a tiny hole in the screen to let out each colour of the spectrum on to another

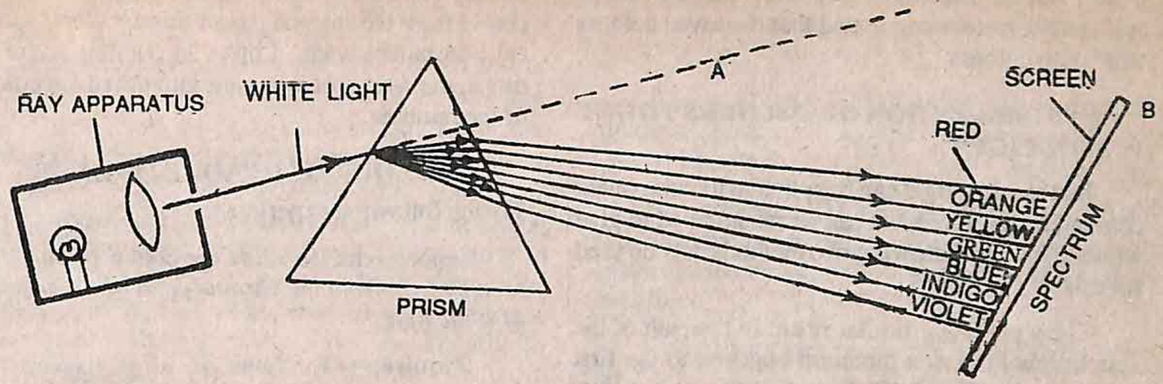


Fig. 7.38

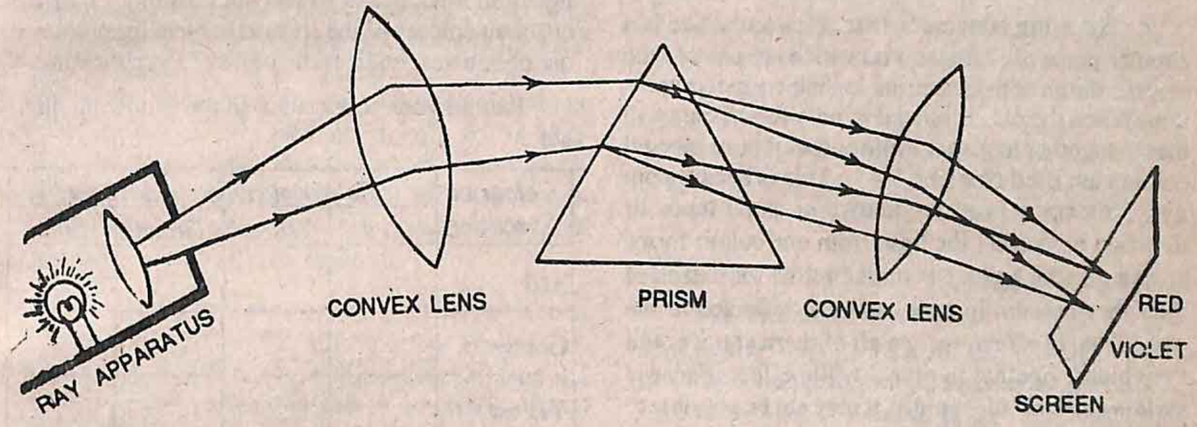


Fig. 7.39

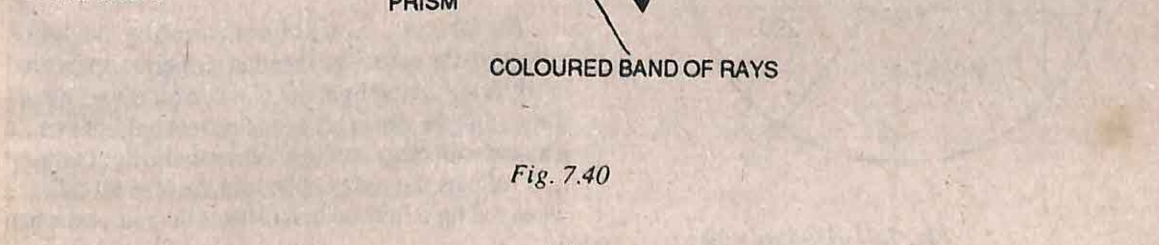


Fig. 7.40

prism. But he discovered that there was no further split, and therefore concluded that the seven colours were pure colours.

7.6 COMBINATION OF COLOURS TO GET WHITE LIGHT :

Just as white light can be split into its component colours, so these colours can be recombined to give white light. The following two methods may be used for this :

1. By placing a similar prism in the path of the split colours but in a direction opposite to the first prism, as in (Fig. 7.40). Note that the two prisms combined behave as the ordinary glass block and the emergent white beam is parallel to the incident white beam.

2. **By using Newton's Disc.** Newton's disc is a circular piece of cardboard on which are painted the seven colours of the spectrum in their correct proportion. When the disc is rotated rapidly the colours will merge together to give a white colour if pure spectral colours are used (See Fig. 7.41). This is because our eyes possess a property known as persistence or duration of vision ; the light from one colour forms an image which persists on the retina until each of the other colours in turn has been reflected to the eye. Thus, in effect, we see all of them at once, and they blend together to give a white effect. Because certain colours fade rapidly, it may not be possible to get a pure white effect.

Rainbows are formed in the same way as the spectrum is formed by a glass prism. They are formed not by glass buy by tiny drops of water suspended in the sky soon after rainfall. The white beam of light comes from the sun and passes through these spherical transparent water drops. On coming out of the drops, the white beam is split into the seven colours of the rainbow.

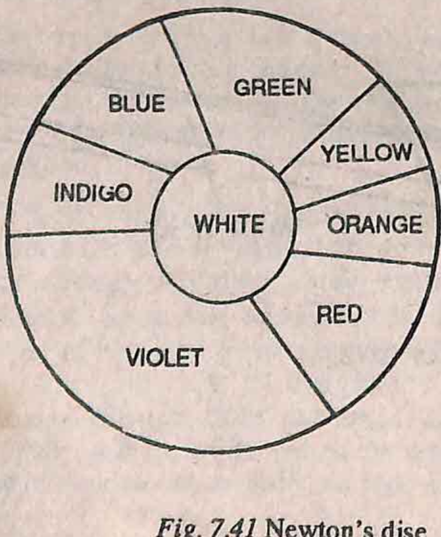


Fig. 7.41 Newton's dise

7.7 COLOUR OF OPAQUE OBJECTS

Try the following experiment.

Experiment. *To study the colour of objects as seen by light from the various parts of the spectrum of white light.*

Requirements. Same as for Experiment to produce spectrum of white light ribbons of different colours.

Procedure. Obtain a pure spectrum of white light and hold all the ribbons in turn in each of the different colours of the spectrum. Note the colour of the ribbon as seen in each colour of the spectrum.

Record your observation in the following manner :

Colour in Spectrum	*Colour of ribbon in daylight*			
	Red	*Yellow*	*Green*	*Blue*
Red				
Orange				
Yellow				
Green				
Blue				
Indigo				
Violet				

The table should show that a red ribbon appears red in the red portion of the spectrum and black in all others, and a white ribbon appears red in the red portion, blue in the blue portion, yellow in the yellow portion and so on.

Explanation. Every object is seen by the light it reflects to the eyes. The fact that a ribbon appears red in white and in red light but black in all other colours shows that the ribbon can only reflect red light while it absorbs all other colours. When white light falls on it, it reflects the red portion and absorbs all others ; when red light falls on it, it reflects the red, and when any other colour falls on it, it absorbs all the colour.

Red, blue and *green* colours, known as the **primary colours,** will reflect only their own colours ; that is, a red object will reflect red light, a blue one will reflect blue and a green one will reflect green. All other colours will reflect their own colours with one or two others. For instance, the yellow ribbon appears yellow in the yellow portion of the spectrum but also appears red in the red and orange in the orange portion. This means that the yellow ribbon, apart from reflecting yellow light, is also able to reflect red and orange.

The experiment explains the colour of opaque objects. *The colour of an opaque object depends on the colour that is reflected by it. This in turn depends on the colour or wavelength of the light incident on it.* The yellow costume put on by an actor on the stage suddenly turns green when green light shines on it and red when red light falls on it, while a red costume suddenly turns black when green light shines on it. The colour generally ascribed to an object is the colour it presents when white light falls on it, that is, in daylight. For example, we say a book cover is red because it appears red in daylight.

You will have had the sad experience of buying a dress or a shirt which appears very beautiful in artificial daylight from the lamps inside the shop and turns out to be some other colour on coming out of the shop.

Coal appears black in all colours, because it cannot reflect any colour ; it absorbs all of them.

7.8. COLOUR OF TRANSPARENT OBJECTS :

Try the following experiment :

Experiment : *To study the colour of transparent objects as seen by light from the various parts of t spectrum of white light.*

Requirements. Same as for Experiment produce spectrum of white light;coloured filte (glass or plastic).

Procedure (*a*) Obtain a pure spectrum of whi light on a white screen. Hold each filter between th prism and the screen. Note the colours that remain o the screen.

Record your observation in the following manner :

Colour of Filter	*Colours seen on the Screen*
Red	
Blue	
Orange	
Green	
etc.	

You will notice that each of the filters allows its own colour to pass through. In particular, the red green and blue (the primary colours) allow *only* thei own respective colours to pass, while each of the other allows one, two or even three other colours t pass along with their own colour. For instance, the orange filter will allow red, orange, yellow and gree to pass through it.

(b) Hold each coloured filter close to your ey and use it to view the different coloured objects yo can find around you : *e.g.*, clothes, books and walls.

Record your observation in the following table

Colour of filter	*Red Book*	*Blue dress*	*Yellow dress*	*Green bottle*	*Pink wall*	*Brown table*	*Coal*
Red							
Green							
Yellow							
Blue							
etc.							

You will notice from the above table that the red book appears red when viewed through the red filter, but black when viewed through any other filters. Also the yellow dress appears yellow through the yellow filter, but, in addition, appears red through the red filter and orange through the orange filter. The green bottle also appears green through a green filter and the blue dress blue through a blue filter. Only the red, the green and the blue filters will give this result while all other colours will give results similar to those of the yellow one.

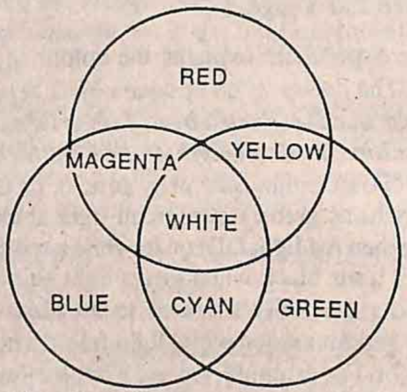
Explanation : *The colour of transparent objects depends on the colour or wavelength of the light which they allow to pass through them (i.e.,* which they transmit). A green glass is green because it allows green light to pass through it and absorbs all other colours. If placed in yellow light it will appear black, as it does not allow yellow light to pass through it, *i.e.*, it absorbs it,

Red, green and blue filters transmit *only* their own colours and absorb all others, whereas other coloured filters transmit their own colours and one or two other colours.

7.9. MIXING OF COLOURED LIGHTS

We have seen that all the visible frequencies mixed together produce white. Interestingly enough, the perception of white also results from the combination of only *red, green,* and *blue light.* If we project these three colours on a screen, overlapping each other, their colours will add to produce white (Fig 7.42).

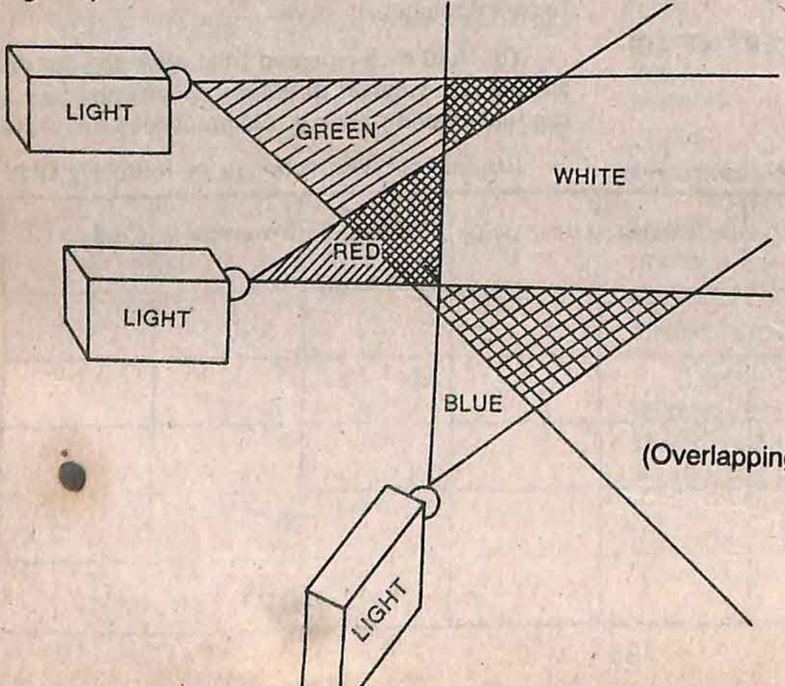
When the beams of light reflect off a white screen, a light seen is an additive mixture because the lights are added together before the observer sees them. If two of the three colours are added, then another colour will be produced (Fig 7.43). By adding various amounts of red, green and blue, the colours to which each of our three types of cones are sensitive, we can produce any colour in the spectrum. For this reason, red, green and blue are called the **primary colours** *or* **additive primary colours.**



(Different colours by overlapping of red, greens and blue lights)

Fig. 7.43

All the rules of colour addition and subtraction can be deduced from the overlapping circles in Fig. 7.43. The additive primaries are the red, green and blue circles, and the **subtractive primaries** (or **secondary colours**) are located where the primary circles overlap. Subtractive primaries (or secondary



(Overlapping of red, green and blue lights)

Fig. 7.42

colours) are produced by mixing two additive primary colours. For example :

Red + Blue = Magenta

Red + Green = Yellow

Blue + Green = Cyan (or peacock blue)

Magenta, Yellow and Cyan are called *subtractive primaries* or *secondary colours.*

Notice that when an additive primary and its opposite subtractive primary combine additively *e.g., green with magenta,* they produce white. From the figure we can see that *blue plus yellow* produces white ; *red plus cyan* does also. *Any two colours that add together to produce white are called* **complementary colours.**

Complementary colours
Green + Magenta = White
Blue + Yellow = White
Red + Cyan = White

7.10. HOW DO WE SEE COLOURS ?

(Colour Sensory Cells in the Eye—Rods and Cones ; Colour blindness.)

The retina is composed of tiny antennae (light sensitive cells) that resonate to the incoming light. There are basically two kinds of antennae, the *rods* and the *cones.* As the names imply some of the antennae are rod-shaped and some cone-shaped. There are three types of cones : those that are stimulated by low-frequency light, those stimulated by intermediate frequencies, and those stimulated by higher-frequency visible light. The rods predominate toward the periphery of the retina, while the three types of cones are denser towards the yellow spot (fovea). The cones are very dense in the fovea itself and since they are packed so tightly, they are much finer or narrower than elsewhere in the retina. *Colour vision is possible because of the cones.* Hence we see colour most acutely by focussing an image on the yellow spot (fovea), where there are no rods. In the human eye, the number of cones decreases as we move away from the fovea. It is interesting that the colour of an object disappears if viewed on the periphery of vision. This can be tested by having a friend enter your periphery of vision with some brightly coloured objects. You will find that you can see the objects before you can see what colour they are.

Another distinguishing feature of the rods and cones is the *intensity of light* (*i.e.,* degree of brightness and darkness) to which they respond. The cones require more energy before they will "fire" an impulse through the nervous system. If the intensity of light is very low, the things we see have no colour. **We see low intensities with our rods.** *Dark-adapted vision is almost entirely due to the rods, while vision in bright light is due to the cones.* Stars, for example, look white to us. Yet most stars are actually brightly coloured. A time exposure of the stars with a camera reveals reds and red-oranges for the " cooler" stars and blues and blue-violets for the "hotter" stars. The star-light is too weak, however, to fire the colour perceiving cones in the retina. So we see the stars with our rods and perceive them as white or, at best, as only faintly coloured. Females have a slightly lower threshold of firing for the cones, however, and can see a bit more colour than males. So if she says she sees coloured stars and he says she does not, she is probably right !

The sensitivity of the rods decreases in bright light. We find that the rods "see" better toward the blue end of the colour spectrum than the cones. The cones can see a deep red where the rods see no light at all. Red light may as well be black as far as the rods can tell. Thus, if you have two coloured objects – say, blue and red – the blue will appear much brighter than the red in dim light, though the red might be much brighter than the blue in bright light. The effect is quite interesting. Try this : In a dark room, find a magazine or something that has colours, and, before you know for sure what the colours are, judge the lighter and darker areas. Then carry the magazine into the light. You should see a remarkable shift betwen the brightest and dimmer colours.

Colour-deficiency :

Colour is not in the world around you ; colour is in your head. The world around you is filled with electromagnetic waves that stimulate the sensation of colour when the vibrations (electromagnetic waves) interact with the cone-shaped receiving antennae in the retina of your eye. *Some people have difficulties in seeing colour, mainly due to cones that are either missing or malfunctioning.* These people are said to be **colour blind or colour deficient.** When they match colours, the match-ups do not correspond to the choices most people make. Although the colours they see are different from what most of us see, they do see colour ; that is why the term *colour-blindness* is no longer used. Very few people are totally colour-deficient, or colour-blind but about 10 percent of the population has difficulty of some-kind in seeing colours. Colour deficiency or *Colour-blindness occurs by inheritance i.e.*, it is a genetic disorder that cannot be cured as of to-day. Colour-deficiency is not usually an all-or-nothing thing. There are many people who actually can see all the colours and who need three hues to match the spectrum but who need *abnormal amounts of one of the hues*. A person who is green-weak sees the spring grass as being a grayish green, but at least is able to perceive green as a distinct colour. A person who is *red-green blind*, however, cannot distinguish green at all, no matter how intense the source is.

John Dalton, founder of the atomic theory, was colour-blind and could not distinguish even between primary colours.

Animals differ in their colour perception. The bee has retinal cone cells that enable it to see colours beyond indigo and violet namely ultraviolet. We human beings are ultraviolet blind. The chicken eye retina has mostly cones and very few rod-shaped cells. The chicken, therefore, needs bright light to see ; that is why it wakes up with the sun, and roosts by sundown.

SOLVED EXAMPLES

Use of Mirror Formula :

The following points will help the students in the solution of numerical problems based on mirror formula:

(*i*) Draw a rough diagram.

(*ii*) Remember the general mirror formula

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

(*iii*) Put the numerical values of u, v and *f* with proper sign.

(*iv*) *Do not assign any sign to the unknown quantity which comes as a result of solution.*

(*v*) The linear magnification is negative for a real image which is inverted and downward and positive for virtual and erect image.

Example 1 :

The focal length of a concave mirror is 15 cm. If the object is placed at a distance of 20 cm from the pole of the mirror, where will the image be formed ? Draw the ray diagram to show the formation of the image.

Solution.

$$u = -20 \text{ cm}$$

$$v = ?$$

$$f = -15 \text{ cm}$$

Now $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

$\therefore$ $\frac{1}{-20} + \frac{1}{v} = \frac{1}{-15}$

$$\frac{1}{v} = -\frac{1}{15} + \frac{1}{20}$$

$$= -\frac{1}{60}$$

$$v = -60 \text{ cm.}$$

The image is formed 60 cm away from the vertex towards the object side.

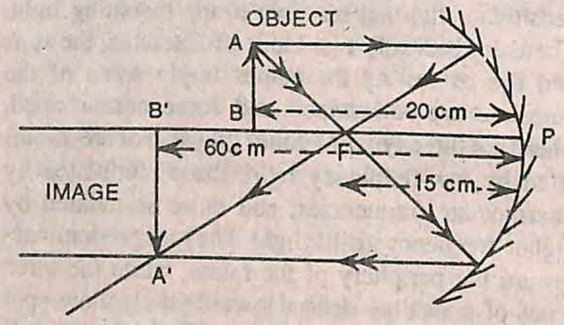


Fig. 7.44

Example 2.

An object is at a distance of 10 cm from the pole of a mirror, and the image of the object is at a distance of 30 cm from the mirror on the same side as the object. Is the mirror concave or convex ? What is its focal length ?

Solution :

$$u = -10 \text{ cm}$$

$$v = -30 \text{ cm}$$

$$f = ?$$

Now $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$

∴ $-\frac{1}{10}-\frac{1}{30}=\frac{1}{f}$

or $-\frac{4}{30}=\frac{1}{f}$

or $f=\frac{-15}{2}=-7{\cdot}5$ cm.

Since the focal length is negative, therefore the mirror is concave one.

Example 3.

A concave mirror of radius of curvature 12 cm forms a real image $\frac{3}{2}$ times the size of a given object. Find the relative positions of the mirror, object and image. With the same mirror and object, can any other position be obtained to give an image of the same size as before ?

Solution :

Radius of curvature = $R=-12$ cm

∴ $f=-6$ cm

$u=?$

$v=?$

Size of the image = $I=3$

Size of the object = $O=2$

∵ $\frac{v}{u}=\frac{I}{O}$

∴ $\frac{-v}{-u}=\frac{3}{2}$ (when the image is real)

or $v=\frac{3}{2}u$

∵ $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$

∴ $\frac{1}{u}+\frac{2}{3u}=\frac{1}{-6}$ (∵ it is a concave mirror)

or $\frac{5}{3u}=-\frac{1}{6}$

or $3u=-30$

or $u=-10$ cm

and $v=\frac{3}{2}u=-10\times\frac{3}{2}=-15$ cm

Second Position. We suppose that the image is virtual.

For a virtual image = $\frac{v}{-u}=\frac{3}{2}$ or $v=\frac{-3}{2}u$

Again,

∵ $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$

∴ $\frac{1}{u}-\frac{2}{3u}=-\frac{1}{6}$

or $\frac{1}{3u}=-\frac{1}{6}$

or $3u=-6$

∴ $u=-2$ cm

Hence $v=3$ cm

This would give a virtual image of the same size as in the first case.

Example 4.

The image formed by a convex mirror of focal length 30 cm is a quarter of the object. What is distance of the object from the mirror.

Solution.:

$f=+30$ cm

$u=?$

$v=?$

Size of the image = $I=1$

Size of the object = $O=4$

∵ $\frac{v}{-u}=\frac{I}{O}$

∴ $\frac{v}{u}=-\frac{1}{4}$

or $v=\frac{-u}{4}$

∵ $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$

∴ $\frac{1}{u}-\frac{4}{u}=\frac{1}{f}$

$$\frac{-3}{u} = \frac{1}{30}$$

$$\mathbf{u = -90\ cm.}$$

Hence the object is 90 cm from the vertex of the convex mirror.

Example 5.

An object 6 cm long is placed 1 metre in front of a concave mirror of 10 cm focal length. Find the nature and the size of the image.

Solution :

$$u = 1 \text{ metre} = -100 \text{ cm}$$

$$v = ?$$

$$f = -10 \text{ cm}$$

Size of the object = O = 6 cm

Size of the image = I = ?

$$\because \quad \frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\therefore \quad \frac{1}{-100} + \frac{1}{v} = \frac{1}{-10}$$

$$\text{or} \quad \frac{1}{v} = -\frac{1}{10} + \frac{1}{100}$$

$$\therefore \quad v = \frac{-100}{9} = -11\frac{1}{9} \text{ cm}$$

Since v is negative, therefore the image is real and inverted.

Now $\frac{-I}{O} = \frac{v}{u}$ where I = Size of the image and O = Size of the object.

$$\therefore \quad \frac{-I}{6} = \frac{\frac{100}{9}}{100}$$

$$I = \frac{-100}{9} \times \frac{1}{100} \times 6 = \frac{-2}{3} \text{ cm.}$$

Example 6.

A candle is held 3 cm away from a concave mirror whose radius of curvature is 24 cm. Where is the image formed ? What is the nature of the image ?

Solution :

Here, Radius of curvature = $R = -24$ cm

$$\therefore \quad f = \frac{R}{2} = -12 \text{ cm}$$

$$u = -3 \text{ cm}$$

$$\because \quad \frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\therefore \quad \frac{1}{v} = \frac{1}{f} - \frac{1}{u}$$

$$= \frac{1}{(-12)} - \frac{1}{(-3)}$$

$$= -\frac{1}{12} + \frac{1}{3} = \frac{1}{4}$$

$$\therefore \quad \boxed{v = 4 \text{ cm}}$$

Thus $m = -\frac{v}{u} = -\frac{4}{(-3)} = \frac{4}{3}.$

Hence the magnitude of m is greater than unity. *Hence the image is 4 cm behind the mirror. It is virtual, magnified and erect.*

Example 7.

How far should one hold an object from a concave mirror of focal length 40 cm so as to get an image twice the size of the object ?

Solution :

Here, $f = -40$ cm

$$\frac{I}{O} = \frac{v}{u} = 2 \text{ (for real and inverted image)}$$

$$\therefore \quad v = 2u$$

$$\because \quad \frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\therefore \quad \frac{1}{u} + \frac{1}{2u} = \frac{1}{-40}$$

$$\text{or} \quad \frac{3}{2u} = -\frac{1}{40}$$

$$\therefore \quad \boxed{u = -60 \text{ cm}}$$

For virtual and erect image

$$\frac{I}{O} = \frac{v}{-u} = 2$$

$$\therefore \quad v = -2u$$

$$\therefore \quad \frac{1}{u} - \frac{1}{2u} = -\frac{1}{40}$$

or $$\frac{1}{2u} = -\frac{1}{40}$$

∴ $$\boxed{u = -20 \text{ cm}}$$

Hence an object should be held at 60 cm from the vertex of the concave mirror for real and inverted image and at 20 cm from the concave mirror for virtual and erect image.

Example 8.

If a concave mirror of focal length 3 cm is held at a distance of 2 cm from a tooth, what is the magnification of the image ?

Solution :

Here, $f = -3$ cm

$u = -2$ cm

$v = ?$

$m = ?$

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\frac{1}{-2} + \frac{1}{v} = \frac{1}{-3}$$

∴ $$\frac{1}{v} = -\frac{1}{3} + \frac{1}{2} = \frac{1}{6}$$

∴ $$v = 6 \text{ cm}$$

$$\text{Magnification} = m = -\frac{v}{u} = -\left[\frac{6}{-2}\right] = 3.$$

Example 9.

An object is at a distance of 5 m from a convex mirror of focal length 10 cm. Where is the image formed and what is its magnification ? Draw the ray diagram to show the formation of the image.See Fig 7.45 for the ray diagram

Solution :

Here, $u = -5 \text{ m} = -500$ cm

$f = 10$ cm

$v = ?$

$m = ?$

Since $$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

∴ $$\frac{1}{-500} + \frac{1}{v} = \frac{1}{10}$$

$$\frac{1}{v} = \frac{1}{10} + \frac{1}{500} = \frac{51}{500}$$

∴ $$v = \frac{500}{51} \text{ cm}$$

$$= 9.8 \text{ cm}$$

$$\text{Magnification} = m = -\frac{v}{u}$$

$$= -\left[\frac{9{\cdot}8}{-500}\right]$$

$$= 0{\cdot}0196.$$

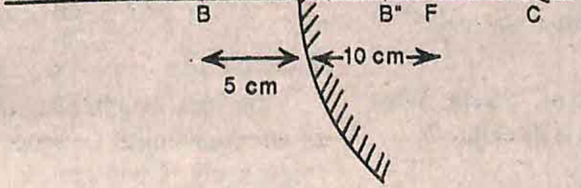
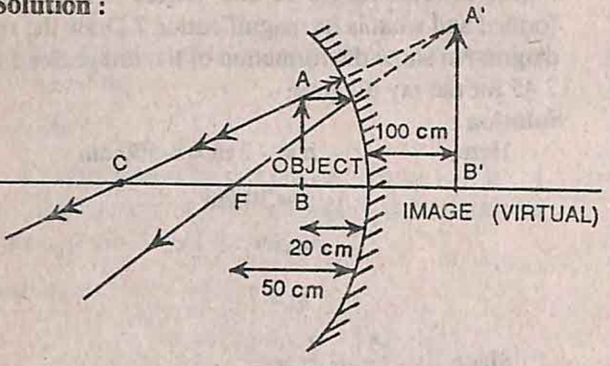


Fig 7.45

Example 10.

An object is located 20 cm in front of a concave mirror of radius of curvature 50 cm. Where is the image formed and what is its nature ? Draw the ray diagram to show the formation of the image.

Solution :



CONCAVE MIRROR

Fig. 7.46

Here, $u = -20$ m

$R = -50$ cm

$$f = \frac{R}{2} = -25 \text{ cm}$$

$v = ?$

Now $$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

$$\therefore \quad \frac{1}{-20} + \frac{1}{v} = \frac{1}{-25}$$

$$\frac{1}{v} = -\frac{1}{25} + \frac{1}{20}$$

$$= \frac{1}{100}$$

$$\therefore \quad v = 100 \text{ cm}$$

Hence the image is virtual and erect.

$$\text{Magnification} = m = -\frac{v}{u} = -\left[\frac{100}{-20}\right] = 5$$

Thus the image is 100 cm behind the mirror, magnified five times and its is virtual and erect.

Example 11.

A thin lens has a focal length of – 25 cm. What is the power of the lens and what is its nature ?

Solution :

Power of a lens (in dioptres)

$$= p = \frac{1}{\text{focal length in metre}}$$

$$= \frac{100}{\text{focal length in cm}}$$

$$= \frac{100}{-25} = -4 \text{ dioptres}$$

It is a concave (or diverging) lens.

Example 12.

A convex lens of focal length 5 cm is used as a simple microscope. What is its magnifying power if the final image is at the distance of distinct vision (25 cm) ? If it is used as eyepiece in a compound microscope with objective of magnifying power 40, what is the magnifying power of the compound microscope ?

Solution :

Magnifying power of a simple microscope

$$= 1 + \frac{D}{f}$$

$$= 1 + \frac{25}{5}$$

$$= 1 + 5 = 6$$

Since, magnifying power of a compound microscope

= magnifying power of the objective × magnifying power of the eyepiece

or $m = m_o \times m_e$

$$= 40 \times 6$$

$$= 240$$

Example 13.

A man whose least distance of distinct vision is 25 cm uses a convex lens of 3 cm focal length as a magnifying glass. Find the magnification he obtains.

Solution :

Here, $D = 25$ cm and $f = 3$ cm

∴ Magnifying power of the magnifying glass

$$= 1 + \frac{D}{f}$$

$$= 1 + \frac{25}{3} = \frac{28}{3} = 9\frac{1}{3}$$

Example 14.

The focal lengths of the object glass and eye lens of an astronomical telescope are 60 cm and 5 cm respectively. Find its magnifying power.

Solution :

Here, $F = 60$ cm and $f = 5$ cm

∴ Magnifying power $= \dfrac{F}{f} = \dfrac{60}{5} = 12.$

Example 15.

It is required to project a 3 cm square slide so as to give 30 cm square picture on a screen at a distance of 11 metre from the slide. What should be the focal length of the projecting lens you would use and where would you place it ?

Solution :

Length of each side of the slide = O = 3 cm

Length of each side of the picture

$$= I = 30 \text{ cm}$$

$$u + v = 11 \text{ m} \quad \text{... (i)}$$

$$\therefore \quad \frac{I}{O} = \frac{v}{-u}$$

$$\therefore \quad \frac{30}{3} = \frac{v}{-u}$$

or
$$v = -10u \quad \text{... (ii)}$$

Putting (ii) in (i), we get

$$-u - 10u = 11$$

$$u = -1 \text{ m} \quad \text{... (iii)}$$

Putting (iii) in (ii), we get,

$$v = 10 \text{ m} \quad \text{... (iv)}$$

Now
$$\frac{1}{f} = \frac{1}{v} - \frac{1}{u} = \frac{1}{10} + \frac{1}{1} = \frac{11}{10}$$

$$\therefore \quad f = \frac{10}{11} \text{ m.}$$

Example 16.

A student with defective eye-sight can see clearly nothing that is further from his eye than 50 cm. What is the number, kind and focal length of the correcting lens that will enable him to see easily and clearly distant object ?

Solution :

Here,
$$u = -\infty$$

$$v = -50 \text{ cm}$$

Power of the lens $= p = ?$

$$\therefore \quad \frac{1}{f} = \frac{1}{v} - \frac{1}{u}$$

$$\frac{1}{f} = \frac{1}{-50} + \frac{1}{\infty}$$

$$\therefore \quad f = -50 \text{ cm}$$

Hence, power of the lens = p

$$= \frac{100}{\text{focal length in cm}} = \frac{100}{-50}$$

$$= \mathbf{-2 \text{ dioptres.}}$$

Thus a concave lens of focal length 50 cm is required. Its power is – 2 dioptres.

Example 17.

A long-sighted person whose nearest distance of distinct vision is 50 cm finds that this distance is reduced to 20 cm by using spectacles. Find the nature and focal length of the lens used.

Solution :

Here,
$$u = -20 \text{ cm}$$

$$v = -50 \text{ cm}$$

$$f = ?$$

$$\because \quad \frac{1}{f} = \frac{1}{v} - \frac{1}{u}$$

$$\therefore \quad \frac{1}{f} = \frac{1}{-50} - \frac{1}{-20}$$

$$= -\frac{1}{50} + \frac{1}{20}$$

or
$$\frac{1}{f} = \frac{3}{100}$$

or
$$f = \frac{100}{3} = \mathbf{33.33 \text{ cm.}}$$

Thus a convex lens of focal length 33.33 cm is required.

Example 18.

An object 60 cm from a lens gives a virtual image at a distance of 2 cm infront of the lens. What is the focal length of the lens ? Is the lens converging or diverging ? Give reason for your answer . Draw the ray diagram to show the image formation.

Solution :

Here,
$$u = -60 \text{ cm}$$

$$v = -20 \text{ cm}$$

$$\because \quad \frac{1}{f} = \frac{1}{v} - \frac{1}{u}$$

$$\therefore \quad \frac{1}{f} = \frac{1}{-20} - \frac{1}{(-60)}$$

$$= -\frac{1}{20} + \frac{1}{60}$$

$$= -\frac{1}{30}$$

$$\therefore \qquad f = -30 \text{ cm.}$$

Since the focal length of the lens is *negative* and it *diverges* the beam of light on refraction in order to give virtual image in front of the lens so the lens is *diverging* or *concave* and its focal length is 30 cm. For ray diagram see fig 7.47

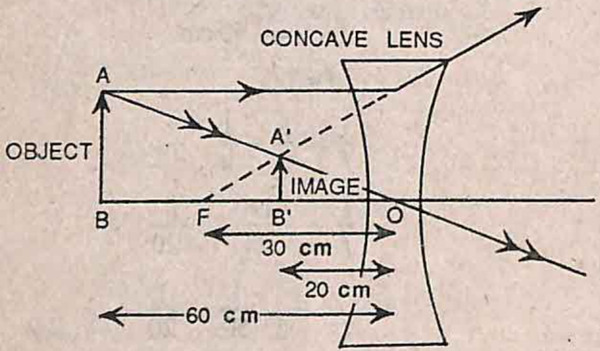


Fig. 7.47

Example 19.

A convex lens has a focal length of +0.1m. Find the image distance when the object distance is (a) 0·5 m ; (b) 0·08 m. Draw the ray diagram in each case to show the image formation.

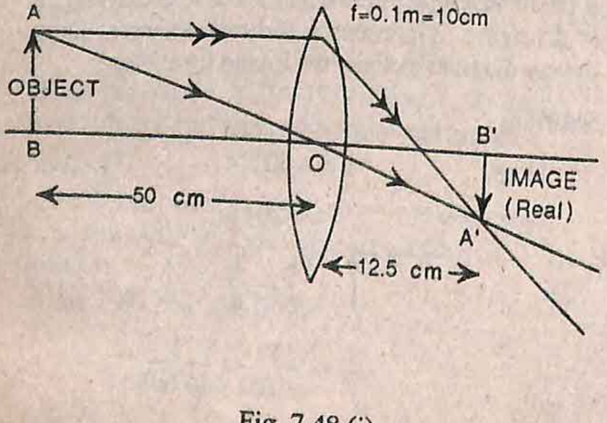


Fig. 7.48 (i)

Solution :

(a) Here, $f = 0.1\text{m} = 10$ cm

$u = -0.5\text{m} = -50$ cm"

$v = ?$

Using the thin lens formula

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

or
$$\frac{1}{v} = \frac{1}{f} + \frac{1}{u}$$

$$\therefore \qquad \frac{1}{v} = \frac{1}{10} - \frac{1}{50} = \frac{2}{25}$$

$$\therefore \qquad v = \frac{25}{2} = \mathbf{12.5cm = 0.125\ m.}$$

Note that v is *positive*, corresponding to a *real image* [Fig 7.48 (*i*)].

(b) Here, $f = 0·1$ m = 10 cm

$u = -0·08$ m = -8 cm

$v = ?$

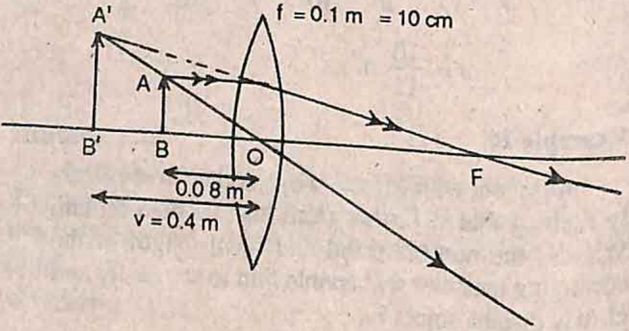


Fig. 7.48 (ii)

Using the thin lens formula

$$\frac{1}{v} - \frac{1}{u} = \frac{1}{f}$$

or
$$\frac{1}{v} = \frac{1}{f} + \frac{1}{v}$$

$$\therefore \qquad \frac{1}{v} = \frac{1}{10} - \frac{1}{8} = -\frac{1}{40}$$

$$\therefore \qquad \mathbf{v = -40\ cm = -0·4\ m.}$$

Here v is **negative**, so the image is **virtual** [Fig 7.48 (*ii*)]

SUMMARY

1. An image formed by rays of light actually passing through the image point is called a real image. Real images are inverted relative to the object and can be larger or smaller than the object. Real image can be obtained on a screen.

   An image formed by rays of light which appear to have diverged from the image point and do not actually pass through that point is called a virtual image. Virtual images cannot be projected on a screen. They are erect with respect to the object ; they can also be enlarged or reduced in size.

2. Besides plane mirrors, we have mirrors which are curved. The laws of reflection hold for the curved mirrors also.

   Spherical mirrors, the surfaces of which are sections of spheres, are commonly used for special purposes. The size and position of the images formed are quite different from those of the images formed by plane mirrors.

3. When the mirror is a portion of the polished *outer* surface of a sphere, it is said to be *convex.* The reflecting surface is curved towards the observer.

   When the mirror is a portion of the polished *inner* surface of a sphere, it is said to be *concave*. Here the reflecting surface is curved away from the observer.

4. The *centre of curvature* is the centre of the sphere of which the mirror forms a part.

   The *aperture* is a measure of the portion of the sphere included by the mirror. Only a small section of the total surface of the sphere is used as the reflecting surface for clear image formation.

   The *vertex* (or the pole) is the centre of the mirror itself.

   The *principal axis* is the line drawn through the centre of curvature and the vertex.

   A *secondary axis* is any other line drawn through the centre of curvature.

   A normal to the surface of a concave mirror is a radius drawn from a point of incidence. (The radius is perpendicular to the tangent to the surface drawn through the point of incidence). In a convex mirror, a normal is a radius produced or extended beyond the mirror.

   The point on the principal axis to which rays parallel to the principal axis converge (or from which they diverge) is known as the *principal focus*. The distance between the principal focus and the vertex is called the *focal length* of the mirror.

5. Focal length of a spherical mirror is half its radius of curvature

$$f = \frac{R}{2}.$$

6. Since incident rays diverge on being reflected, convex mirrors are nowr as *diverging* mirrors.

7. Graphical Method (concave mirror) :

   We can construct the image formed by a concave mirror by locating the images of enough different points. Concave mirror images may be grouped into six cases.

   Case 1. *Object at infinite distance.*

   The image formed by a concave mirror is a point at the principal focus.

   Case 2. *Object at finite distance beyond the centre of curvature.*

   The image in this case is real, inverted, reduced and located between the centre of curvature and the principal focus.

   Case 3. *Object at the centre of curvature.*

   The image is real, inverted, the same size as the object, and located at the centre of curvature.

   Case 4. *Object between the centre of curvature and principal focus.*

   The image is real, inverted, enlarged and located beyond the centre of curvature.

   Case 5. *Object at principal focus.*

   The image is real, inverted, highly enlarged and lies at infinity.

   Case 6. *Object between principal focus and mirror.*

   The image is virtual, erect, enlarged and located behind the mirror.

8. In constructing ray diagrams for convex mirrors we proceed as for concave mirrors except that the four rays of importance are the following :
   - (i) A ray that is parallel to the axis and which is reflected as if it came from the virtual principal focus of the mirror.
   - (ii) A ray that is heading toward the virtual principal focus and which is reflected parallel to the principal axis (by the principal of reversibility of rays).
   - (iii) A ray that is heading toward the vertex of the mirror and which is reflected so that the angle of reflection with respect to the principal axis is equal to the angle of incidence.
   - (iv) A ray that is heading toward the centre of curvature of the mirror and which is reflected directly back on itself.

   These four rays enable the image of any point on an object to be located for a convex mirror. In a convex mirror, all images are virtual, erect, smaller than the object and located behind the mirror between the vertex and the principal focus. The size of the image increases as the object moves closer to the mirror, but it can never become as large as the object itself.

9. A simple relationship exists between the distance of an object (u) from a curved mirror, the distance of its image (v) and the focal length (f) of the mirror. This relationship, known as the *mirror equation* is as follows :

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

   The mirror equation is applicable to all concave and convex mirrors.

10. The image of an object formed by a spherical mirror can be larger or smaller than the object. It may be inverted or erect, real or virtual. It depends upon the position of the object relative to the mirror and nature of the spherical mirror employed.

11. Lateral magnification is the ratio of the height of the image to that of the object.

$$m = \frac{I}{O} = -\frac{v}{u}$$

   The magnitude of m can be greater or less than unity depending upon the values of u and v.

12. *A lens* is a piece of transparent material, usually glass, bounded by two spherical surfaces. Essentially, there are two types of lenses :
   - (i) *Convex lenses* which are thicker at the centre than at the edges, and
   - (ii) *Concave lenses* which are thinner at the centre than at the edges.

   The convex lens *converges* a parallel beam of light on refraction and is, therefore, also known as a *converging lens*. On the other hand, a concave lens diverges a parallel beam of light on refraction and is, therefore, also called a *diverging lens*.

13. *Convex lens :*
   - (i) has a real focus,
   - (ii) produces real and inverted images when the object is further from the lens than the focus. When the object is nearer to the lens than the focal length, an erect, virtual and magnified image is obtained [magnifying glass].

   Concave lens :
   - (i) has a virtual focus,
   - (ii) produces an erect, virtual and diminished image of an object, and
   - (iii) a virtual object may produce a real image.

14. *Image formation (Graphical method) :* In accurate drawing of images with both types of lenses (a) the lens is represented *thin*, (b) A ray through the centre of the thin lens (*i.e.,Optical Centre*) passes straight through the lens, (c) a ray parallel to the principal axis is refracted through the focus.

15. *Lens formulae :*
   - (i) *New Cartesian sign convention :*

$$\boxed{\frac{1}{v} - \frac{1}{u} = \frac{1}{f}}$$

   - (ii) For a convex lens ; f is +

     For a concave lens ; f is –
   - (iii) The linear magnification, $m = \frac{v}{u} = 1 - \frac{v}{f}$.

16. The focal length of a lens depends upon the refractive index of the material from which it is made and the curvatures of the two surfaces. More the curvature, shorter the focal length.

17. *Power* (p) of a lens is the reciprocal of its focal length (f)

$$p = \frac{1}{f}$$

If the focal length (f) is measured in *metres*, the power of the lens is in *dioptres*.

If we take a number of thin lenses and place them in the close contact, then the power of the combination p is the algebraic sum of powers of the individual lenses, *i.e.*,

$$p = p_1 + p_2 + p_3 + \ldots.$$

18. **The eye.** This contains (i) a crystalline lens, (ii) ciliary muscles which control the radii of the lens surfaces and hence the focal length, (iii) the retina, a sensitive "screen" at the back of the eyeball, covered with nerves linked to the optic nerve. The iris of the eye is a diaphragm with a circular (black) hole in the middle called the pupil ; the colour of an eye is the colour of the iris. The aqueous humour is a weak salt solution in front of the lens ; the vitreous humour is a gelatinous substance between the lens and retina. The cornea is the tough transparent spherical bulge in front of the lens.

The use of two eyes gives a three-dimensional view, bringing with it a sense of distance.

19. **Far and Near Points :** *Accommodation.* A person with normal vision can see clearly objects a very long way off. The *far* point of a normal eye is thus " infinity".

The nearest point which the eye can see distinctly is about 25 cm for normal vision. The distance concerned, D, is called the *least distance of distinct vision* of the eye.

With normal vision, the eye is fully relaxed or "unaccommodated" when viewing objects at infinity. When the object is at the least distance of distinct vision and is focused by the eye, the ciliary muscles are fully strained and the eye is said to be "fully accommodated".

20. *Myopia* or *Shortsightedness* : In this defect the far point is near the eye, and rays from infinity now come to a focus in front of the retina.

Correction is made by a *diverging* lens, whose focal length is equal to the distance of the far point from the eye.

Hypermetropia or *Far sightedness.* In this defect of vision, the far point of the eye is normal but the near point is further from the eye than 25 cm.

Correction is made by a suitable *converging lens.*

21. A *microscope* magnifies the image of an object enabling us to study its details which are too small to be seen by naked eyes.

Linear magnification (m) of a *simple microscope* or *magnifying glass* is given by

$$m = 1 + \frac{D}{f} = 1 + \frac{25}{f}$$

where D is *numerically* the *least distance of distint vision* and f is the focal length.

22. *Compound microscope.* This has two converging lenses, both of short focal length. In using the instrument.

(i) the object is placed *slightly further* from the objective than its focal length ;

(ii) the real image formed is viewed through the eye piece, acting as a magnifying glass. The magnifying power or magnification $m = m$ objective Xm eye piece. It is the product of magnifying powers of the objective and the eye piece, $m = LD/F.f$ where L is the length of the tube; F is the focal length of the objective; f is the focal length of the eye piece and D is the distance of distinct vision.

23. *Astronomical Telescope.* It is a device for viewing distant objects. It consists of two converging lenses. The one which receives the light from the object is called the *objective*, the other lens through which we view the object is called the *eyepiece.*

When the final image is at infinity, the telescope is said technically to be in *normal adjustment.*

The magnifying power of the telescope, in normal adjustment, is given as

$$m = \frac{\text{Focal length of the objective}}{\text{Focal length of the eye piece}} = \frac{F}{f}$$

The distance between the lenses = $F + f$.

Astronomical telescope. *Final image at near point.* The final image is now virtual and distant D from the eye piece ; the image produced by the objective is thus nearer to the eye piece than its focal length.

24. The splitting of a beam of white light into different components when it passes through a transparent medium, such as a glass prism, is called *dispersion of light*. The refractive index of a given material depends on the spectral colour of light.

25. Rainbow is a display of colours that occurs just after rain when the sun is shining. There are innumerable tiny droplets of water in the atmosphere and each of these split the sunlight into its spectrum which forms a rainbow.

26. An opaque object reflects certain colours and absorbs the rest. A red rose in the day time appears red because it reflects red light and absorbs other colours.

Similarly, the colour of light in which we view an object also affects the colour of that object. For example, a red rose when illuminated by blue light would appear black as there is no red light to be reflected by the rose.

27. *Red, blue* and *green* are the three **primary** colours. All other colours are *secondary colours* (or *subtractive primaries*) because they can be obtained by mixing two or all the three primary colours in proper proportion.

Any two colours that add together to produce white are called *complementary colours*.

28. The retina of the eye has a large number of *cone-shaped* and *rod-shaped cells*. Only the cone-shaped cells are sensitive to lights of different colours. We see low intensities with rod-shaped cells.

Some people do not prossess some cone cells that respond to certain colours. This defect occurs by inheritance *i.e.,* it is a genetic disorder that cannot be cured as of to-day. These people are said to be *colour-blind*. They can see well otherwise; their only problem is the lack of ability to distinguish colours.

QUESTIONS

[A] Objective Type Questions

1. An object is 30 cm from a concave spherical mirror whose focal length is –20 cm. The image is
   - (a) virtual and enlarged
   - (b) virtual and reduced in size
   - (c) real and reduced in size
   - (d) real and enlarged.

2. The radius of curvature of the mirror in Q. (1) is .... cm.

3. Which mirror has a wider field of view :
   - (a) concave mirror
   - (b) convex mirror
   - (c) plane mirror.

4. An image formed by a convex mirror is always
   - (a) virtual, erect and diminished
   - (b) virtual, real and magnified
   - (c) real, inverted and diminished
   - (d) real, erect and magnified.

5. The image formed by a concave mirror is seen to be virtual, erect and larger than the object. The position of the object must then be
   - (a) betwen the mirror and its focus
   - (b) between the focus and the centre of curvature.
   - (c) at the centre of curvature
   - (d) beyond the centre of curvature.

6. In the case of a concave mirror, match the items in Column B against the items in Column A.

	Column A (Position of object)		**Column B** (Position of image)		**Column A**		**Column B**
(a)	Ver far away	(i)	Very far away	(e)	At F	(v)	At F
(b)	At C	(ii)	Between *F* and the vertex	(f)	Beyond C	(vi)	Beyond C on the same side as the object.
(c)	Between *F* and the vertex	(iii)	At C			(vii)	On the other side of the mirror *i.e.,* behind
(d)	Between *F* and *C*	(iv)	Between *F* and C				

7. Where should an object be placed so that a real and inverted image of the same size is obtained, using a convex lens ?
   (a) Between the lens and its focus.
   (b) At the focus.
   (c) At twice the focal length
   (d) At infinity.

8. The human eye forms the image of an object at its
   (a) cornea
   (b) Iris
   (c) pupil
   (d) retina.

9. The change in focal length of an eye lens to focus the image of objects at varying distances is done by the action of the
   (a) pupil.
   (b) cilliary muscles.
   (c) retina.
   (d) blind spot.

10. The beams of light, one red, and the other green fall on a the same spot on white screen. The colour on the screen will appear to be
   (a) magenta
   (b) blue
   (c) cyan
   (d) yellow.
   (Choose the correct answer).

11. A red apple and a blue flower on a green stalk are placed in a dark room and then illuminated with light coming from a yellow filter. The appearance of the articles will be

	apple	*flower*	*stalk*
(a)	yellow	yellow	yellow
(b)	black	green	blue
(c)	green	blue	red
(d)	red	black	green
(e)	blue	red	black

12. A person with defective vision can only accommodate over the range of 20 cm to 400 cm from his eyes. This person is suffering from
   (a) myopia (short sight)
   (b) hypermetropia (long sight)
   (c) a combination of myopia and hypermetropia
   (d) lack of accommodating power

13. The most suitable correcting lenses for the person in Q. (12) would have a power, in dioptres (m^{-1}) of
   (a) – 4.00
   (b) – 0.25
   (c) + 0.25
   (d) + 1.00
   (e) + 4.00

14. A long-sighted person cannot see clearly objects nearer to his eye than 50 cm. To enable him to read a book 25 cm away, he should use spectacle lenses whose power in dioptres (m^{-1}), is

- (a) – 6
- (b) – 4
- (c) – 2
- (d) + 2
- (e) + 4

15.

Assertion		**Reason**
A short-sighted person *whose far point is 50 cm from his eyes needs a diverging* spectacle lens of focal length 50 cm.	because	his unaided eye tends to form an *image of a distant object behind the retina.*

Answer

- (a) if both assertion and reason are true statements and the reason is a correct explanation of the assertion.
- (b) if both assertion and reason are true statements but the reason is *not* a correct explanation of the assertion.
- (c) if the assertion is true but the reason is a false statement
- (d) if the assertion is false but the reason is a true statement
- (e) if both assertion and reason are false statements.

16. Convex lenses always
    - (a) have two spherical surfaces
    - (b) are thinner in the middle than at the edges
    - (c) are thicker in the middle than at the edges.

17. An object is more than one focal length away from a converging lens. As the distance of the object from the lens increases the distance of the image from the lens
    - (a) increases
    - (b) decreases
    - (c) remains the same.

18. In question (17), the size of the image
    - (a) increases
    - (b) decreases
    - (c) remains the same.

19. When a person uses a convex lens as a simple magnifying glass, the object must be placed at a distance from the lens of
    - (a) a little less than one focal length
    - (b) a little more than one focal length
    - (c) a little less than two focal lengths
    - (d) a little more than two focal lengths

20. The image produced by a concave lens is
    - (a) always virtual and enlarged
    - (b) always virtual and reduced in size
    - (c) always real

(d) sometimes real, sometimes virtual.

21. Real images formed by single convex lenses are always
    - (a) on the same side of the lens as the object
    - (b) inverted
    - (c) erect
    - (d) smaller than the object.

22. A virtual image is formed by
    - (a) a slide projector in a cinema hall
    - *(b) the ordinary camera*
    - *(c) a simple microscope.*

23. A convex lens produces a virtual image. The distance of the object from the lens
    - (a) must be less than one focal length
    - (b) may be more than two focal lengths
    - (c) may be between one and two focal lengths
    - (d) must be two focal lengths.

24. An object is placed 12 cm from a convex lens whose focal length is 10 cm. The image must be
    - (a) virtual and enlarged
    - (b) virtual and reduced in size
    - (c) real and reduced in size
    - (d) real and enlarged.

25. An object is placed 20 cm from a concave lens whose focal length is 10 cm. The image must be
    - (a) virtual and enlarged
    - (b) virtual and reduced in size
    - (c) real and reduced in size
    - (d) real and enlarged.

26. An object is placed 25 cm from a convex lens whose focal length is 10 cm. The image distance is .... cm.

27. If the object in Q. (26) is 4 cm tall, the height of the image is .... cm.

28. The distance of an image from a convex lens is the same as that of the object. The distance of the object from the lens
    - (a) must be less than one focal length
    - (b) may be more than two focal lengths
    - (c) may be between one and two focal lengths
    - (d) must be two focal lengths.

29. The pupil in the eye corresponds to the ...... in the camera.

30. A camera is used to photograph a distant object. If the focal length of the lens is 'f' then the distance of the film from the lens should be
    - (a) slightly more than $2f$
    - (b) slightly less than $2f$
    - (c) slightly more than f
    - (d) slightly less than f.

31. The distance of distinct vision for a normal eye is
   (a) 25 cm
   (b) 25 m
   (c) 0.25 cm
   (d) 2·5 cm.

32. A convex lens has a focal length of 20 cm. Its power in dioptres is
   (a) 2
   (b) 5
   (c) 0.5
   (d) 0·2.

33. Myopia is corrected by using
   (a) a convex lens
   (b) a concave lens
   (c) a plane mirror
   (d) a convex mirror
   (e) a concave mirror.

34. The objective of a compound microscope is a
   (a) Convex lens with large aperture and large focal length than eye-piece
   (b) Convex lens with a small aperture and small focal length than eye-piece
   (c) Convex lens with a small aperture and large focal length than eye-piece.

35. The power of a lens is –5*D*, its focal length is
   (a) 2·0 m
   (b) –0·2 m
   (c) 20·0 m
   (d) 5 m.

[B] Very Short Answer Questions :

1. What is a convex lens ?
2. Does a concave lens produce the same type of image as a convex lens ?
3. What happens to a ray of light when it passes through the optical centre of a lens ?
4. What type of image is formed by a converging lens when the object lies between principal focus and the optical centre of the lens ?
5. What is the nature of the image formed by a diverging lens ?
6. What is power of a lens ?
7. What is the power of a glass plate ?
8. What is the position of near point for a normal eye ?
9. What is the position of far point for a normal eye ?
10. What is the expression for the magnifying power of a simple microscope ?
11. An optician has lenses of power

$X = +5D$

$Y = -5D$

$Z = -0{\cdot}5D.$

Which one has maximum focal length ?

12. An old woman is advised to use lenses of power + $2{\cdot}5D$. What defect of vision is she suffering from ?

13. A 12 year old boy is enable to see a tree beyond a distance of 400 cm, but can see the nearby objects very well. What is this defect of vision called ? What is his far point ?

14. Does light travel faster in air or in water ?

15. Define dispersion of white light.

16. What is spectrum of white light ?

17. What will a red flower look like in yellow light ?

18. Does light travel in vacuum ? (Hint : Yes]

19. Is light an electromagnetic wave ? (Hint : Yes)

20. Power of Ist lens is 4 dioptres and that of the 2nd lens is –10 dioptres. What is the power of the combination ?

21. Out of two convex lenses of focal length 100 cm and 15 cm which one will you prefer for using as a simple microscope ? (Hint : One of f = 15 cm.] [*A.I.S.S. 1987]*

22. What type of image is formed by a convex mirror ?

23. What type of image is formed by a concave mirror when the object lies between the principal focus and the pole of the mirror ?

24. What is the relationship between the focal length and the radius of curvature of a spherical mirror ?

25. What is the radius of curvature of a plane mirror ?

26. What is the focal length of a concave mirror of –30 cm radius of curvature ?

27. A concave mirror of –20 cm focal length forms an image of the same size as the object, what is the position of the object ?

28. Can a converging lens form a virtual image smaller than the size of the object ?

29. Can a diverging lens form a virtual, magnified image of an object ?

30. Name two optical instruments that make use of convex lenses.

31. What is the type of lens used to correct myopia or shortsightedness ?

32. What is the type of lens used to correct hypermetropia or longsightedness ?

Short Answer Type and Essay Type Questions

1. (a) What is a spherical mirror ?
   (b) Distinguish between a concave mirror and a convex mirror.
   (c) How can you tell the difference between a concave and a convex mirror by looking at your face in

each ?

2. (*a*) Define ; Principal axis ; pole ; principal focus ; centre of curvature ; focal length of a spherical mirror giving diagram.
   (*b*) What is the relationship between radius of curvature and focal length of a spherical mirror ?

3. Describe how a concave mirror can be used (*a*) to burn a piece of tissue paper, (*b*) to send out a parallel beam of light.

4. Use diagrams to show why concave mirrors are called converging mirrors while convex mirrors are called diverging mirrors.

5. Describe the series of images formed by (a) a concave mirror, (b) a convex mirror, as the mirror is moved from a position near the face to about 100 cm away.

6. (a) Mention the various uses of spherical mirrors.
   (b) What advantages, as a driver's mirror, does a convex mirror have over a plane mirror ?

[A.I.S.S.E. 1979, 1986]

7. (a) What is magnification produced by a spherical mirror ?
   (b) What changes would you observe in your image as you move nearer to (*a*) a plane mirror, (*b*) a concave mirror, (*c*) a convex mirror ?

8. (a) Why do the images of trees appear to be inverted in water by the river-side ?
   (b) For what purpose does a surgeon use a concave mirror ?
   (c) Where should an object be placed infront of a concave mirror to obtain its magnified erect image ?

[A.I.S.S.E. 1982]

9. You are given three mirrors of equal size one concave, one convex and one plane. How will you identify them without touching their surface ?

10. Using a concave mirror, a screen and a measuring scale in broad day light, how will you find the height of a tree ?

Hints :

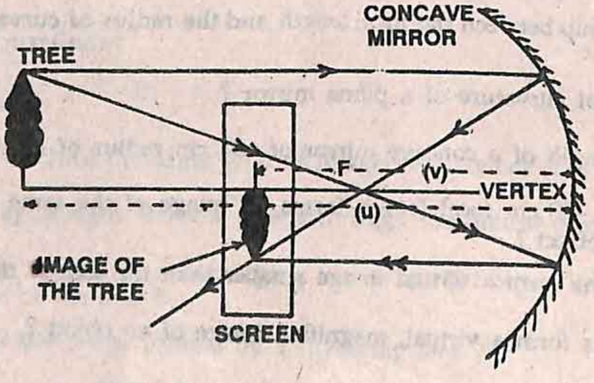


Fig. 7.49

$$\frac{\text{Size of the image}}{\text{Size of the object}} = \frac{I}{O} = \frac{v}{u}$$

11. (a) Construct a ray diagram to show the formation of an image by a convex mirror.
    (b) Describe fully the image that is formed.

12. What kind of mirror produces (a) a short, fattened image ; (b) a tall, thin image ?

13. What kinds of mirrors could be used and where should the object be placed to produce
    (a) an enlarged real image
    (b) a reduced real image
    (c) a real image, the same size as the object
    (d) an enlarged virtual image
    (e) a reduced virtual image?

14. Construct a ray diagram to show the formation of an image by a concave mirror when the object is at a finite distance beyond the centre of curvature. Describe fully the image that is formed.

15. Construct a ray diagram to show the formation of an image by a concave mirror when the object is between the principal focus and the centre of curvature. Describe fully the image that is formed.

16. Starting from a large distance, a flame is slowly moved towards a convex mirror. Comment on how the size and position of the image change.

[A.I.S.S. 1987]

17. What is a lens ? What is the difference between a concave lens and a convex lens ?

18. Define : Principal axis ; optical centre ; principal focus ; and focal length of a lens. Draw diagrams to illustrate your answer.

19. Discuss the size, position and nature of the image formed by a convex lens when the object lies
    (i) at infinity
    (ii) beyond 2f where f is the focal length of the lens
    (iii) at 2f
    (iv) between *f* and 2*f*
    (v) at *f*
    (vi) between the optical centre and the focus.

20. Discuss the size, position and nature of the image formed by a *concave lens* when the object lies
    (a) at infinity
    (b) at *f* where *f* is the focal length.

21. (a) Describe the construction of human eye. Draw labelled diagram.
    (b) Compare human eye with photographic camera.

22. What are the two main defects of vision ? How are they corrected ? *(AI.S.S.E. 1982)*

23. (a) What is a microscope?
    (b) When does a convex lens act as a simple magnifying glass (or simple microscope) ? Draw its labelled disgram. Derive an expression for its magnifying power. Define magnifying power of a microscope.
    (c) What is the difference between a simple miscroscope and a compound microscope?

24. (a) What is a telescope?
    (b) Describe the working of an astronomical telescope. What features make its magnifying power large?

25. Explain :
    (a) If you were supplied with four convex lenses of focal lengths 100 cm ; 25 cm ; 3 cm and 2 cm respectively, state which lenses you would select for constructing
        (i) an astronomical telescope,
        (ii) a simple microscope,
        (iii) a compound microscope?

(b) What alteration in the astronomical telescope is required to increase
  (i) magnification,
  (ii) brightness of image ?

26. (a) Name the Scientific terms which denote the following :
  (i) The power of the eye which enables it to focus objects at varying distances away.
  (ii) Defect of the eye due to which a person cannot see the distant object clearly.
  (iii) Sensitive screen in the eye for the reception of images.
  (iv) The point for which the eye is focussed when at rest.
  (v) The nearest point to the eye at which a small object can be clearly seen.
  (vi) The distance of the point from the eye at which we can see objects most clearly.
  (b) State the Physical principle made use of in the case of Magnifying glass.
  (c) Answer the following questions :
  (i) Is the image on the retina of the eye real or virtual ?
  (ii) What is circular aperture of the eye called ?
  (iii) In hypermetropia does the crystalline lens become more divergent or more convergent ?
  (iv) What is normally the distance of distinct vision ?

27. Which of the following, as normally used, form real images :
  (i) eye
  (ii) microscope
  (iii) plane mirror
  (iv) concave shaving mirror.

28. Show that a real image formed by a man by a converging lens only inverts him but that he and his image still have the same right hand. Show that exactly the reverse is true for an image formed by a plane mirror.

29. Describe the image formation in a compound microscope. Draw its labelled diagram.

30. What name is given to the splitting of white light into its various colours by a prism ? What causes this splitting ?

31. (a) Explain why one book appears red to the eye and another green ?
  (b) Explain why a book appears red when seen through a red transparent piece of glass but black when seen through a green one.

32. Draw a ray diagram for an object seen through
  (a) a simple microscope.
  (b) a compound microscope. *[A.I.S.S. 1986]*
  (c) an astronomical telescope.

[A.I.S.S. 1987]

33. How does a normal eye see clearly objects at various distances ? Name one of the common defects of vision and type of the lens used to remove it. *[AI.S.S. 1987]*

34. How is the amount of light entering the eye controlled ? What change is made in the eye to enable it to focus on objects situated at different distances ?

35. Why does it take some time to see objects in a dim room when you enter the room from bright sunlight outside ?

36. What is
  (i) shortsightedness ?

(ii) longsightedness ?

How can these defects be corrected ?

37. What are

  (i) primary colours ?
  (ii) secondary colours ?
  (iii) complementary colours ?

38. What colours do we get when

  (i) Red, green and blue are mixed ?
  (ii) Yellow and blue are mixed ?
  (iii) Red and blue are mixed ?
  (iv) Red and green are mixed ?

39. (a) How do we see colours ?

  (b) What is meant by colour-blindness ? What is it due to ?

PROBLEMS

1. A concave mirror of focal length 10 cm is placed at a distance of 0.35 m from a wall. How far from the wall should an object be placed to get its real image on the wall ? Draw a scale diagram and use a scale of 1 : 5.

[Ans. 0.21 m]

2. A concave mirror forms a virtual image three times the size of the object, when the distance between the object and the mirror is 0.1 m. Find the position and size of the image when an object 3 cm high is placed 0.4 m from the mirror.

[Ans. 0.24 m from the mirror ; real ; inverted and 1·8 cm high].

3. The image formed by a convex spherical mirror of focal length 0.3 m is a quarter of the size of the object. What is the distance of the object from the mirror ? [Ans. 0·9 m]

4. A concave mirror has a radius of 1 m. Where must the object be placed so that its image is formed at a distance of 1 m from the pole of the mirror ? Draw a scale diagram and use a scale of 1 : 20. [Ans. 1 m]

5. An object 2·5 cm long is placed on the axis of a concave mirror of 30 cm radius of curvature at distance of 10 cm from it. Find the position, size and nature of the image formed.

[Ans. Virtual erect 30 cm behind the mirror ; 7·5 m]

6. An object is 10 cm from a convex mirror of focal length 20 cm. Find the position and nature of the image. Draw a scale diagram. [Ans. 6·67 cm ; Virtual and erect]

[D.B.S.S. 1978]

7. An object is placed at a distance of 4 cm from a concave mirror of focal length 12 cm. Find the position and nature of image. Draw a scale diagram. [Ans. 6 cm; Virtual and erect]

[D.B.S.S. 1979]

8. A concave mirror produces a real image of height 2 cm of an object of height 0·5 cm placed 10 cm away from the mirror. Find the position of the image and focal length of the mirror.

[Ans.–40 cm; – 8 cm]

[D.B.S.S. 1980]

9. An object 1 cm high is placed on the axis of and 15 cm from a concave mirror of focal length 10 cm. Find the position, nature, magnification and size of the image.

[Ans . 30 cm ; Real and Inverted ; –2 and 2 cm]

[D.B.S.S. 1981]

10. The focal length of a concave mirror is 6 cm. An object is placed at a distance of 10 cm from its vertex. Where is the image formed ? [Ans . 15 cm away from the vertex towards the object side]

11. A convex mirror of focal length 10 cm is given. If an object is placed 15 cm away from the vertex of the mirror, where is the image formed and what is the magnification. [Ans. 6 cm ; 0·4]

12. A convex mirror has a focal length of 20 cm. An image is produced which is two–thirds of the length of the object. Determine the object distance from the mirror. [Ans. 10 cm]

13. The image of an object in a concave mirror of radius of curvature 20 cm is erect and is formed 30 cm from the mirror. Calculate the object distance from the mirror and the magnification. [Ans. 7.5 cm ; 4]

14. An object and its image in a concave mirror are the same height when the object is 6·4 cm from the mirror. What is the focal length of the mirror ? [Ans. 18.2 cm]

15. Two lenses, one of focal length 25 cm (a convex lens) and another of focal length –10 cm (a concave lens) are placed in contact. What is the (i) power of the combination and (ii) focal length of the combination ? What type of lens the combination acts ? [Ans. (i) – 6 dioptres ; (ii) – 16·67 cm ; concave lens]

16. Suppose that the distance from the eye lens to the retina is 2 cm. What is the focal length of the eye lens system in viewing a distant object ? An object is at the normal near point ? [Ans. 2·0 cm; 1·83 cm]

17. What must be the focal length of the lens in a projector if the image is to be 10 times the size of the object when projected on a screen 5 m away ? [Ans. 45·5 cm]

18. In a simple box camera the distance from the lens to the film is 0·1 m. If the focal length of the lens is 9·50 cm, where must an object be placed to give the best image on the film ? [Ans. 1·90 m from the lens]

19. A certain magnifying glass gives an image of the sun at a distance of 3·0 cm from the centre of the lens. What is the approximate magnifying power of the lens ? [Ans. 30]

20. What is the magnifying power of an astronomical telescope having a 1·00 diopter objective and 30-diopter eye piece lens ? [Ans. 8·33]

21. A person whose distance of distinct vision is 14 cm uses a lens of 5 cm focal length to magnify a small object. What is the distance of the object when in focus and what magnification is obtained ? [Ans. 3·75 cm ; 4]

22. A short-sighted student sees objects most distinctly at a distance of 15 cm. He wants to see a black board at a distance of three metres. What must be the nature of the lens he requires ? [Ans. Concave lens of focal length of – 15·8 cm]

23. A convex lens of 5 cm focal length is placed at a distance of 4 cm from an object. Find the position and relative size of the image. Draw a scale diagram. [Ans. –20 cm ; 5 times the object]

24. It is required to throw an image magnified 29 times on a screen placed at a distance of 6 m from the object. Find the focal length and nature of the lens required. [Ans. 19·33 cm ; convex]

25. Find the distance at which an object should be placed in front of a convex lens of focal length 10 cm to obtain an image of double of its size. Draw a scale diagram. [Ans. 15 cm]

26. An object is placed at a distance of 10 cm, in front of a concave lens of focal length 20 cm. Find the nature and positon of the image formed by the lens. Draw a scale diagram. [Ans. –6·66 cm ; virtual and erect]

27. A convex lens forms an inverted and real image at a distance of 30 cm from its optical centre of an object placed at a distance of 80 cm from it. From the focal length of the lens. Draw a scale diagram. [Ans. 21·8 cm]

28. Find the position and the nature of the image of an object 5 cm high and 10 cm infront of a convex lens of focal length 6 cm. *[A.I.S.S.E. 1986]*

[Ans. 15 cm ; real ; 7·5 cm]

29. A small object is so placed infront of a convex lens of 5 cm focal length that a virtual image is formed at a distance of 25 cm. Find the magnification as well as the magnifying power.

[Ans. 5, 6]

[D.B.S.S. 1981]

30. A lens has a power of –2·5 *D*. What is the focal length and nature of the lens.

[Ans. –40 cm ; concave lens]

[A.I.S.S.E. 1986]

□ □

CHAPTER — 8

HEAT

Learning Objectives :

At the completion of this Chapter, you should be able to grasp :

1. the concept of heat — a form of energy — its S.I. unit.
2. the relationship between mechanical work and heat produced.
3. the concept of temperature, its relationship with heat (*i.e.,* heat is the cause and temperature its effect) and its measurement by a thermometer.
4. the concept of specific heat and its determination by thermal equilibrium.
5. the effects of heat — thermal expansion, change of state and idea of latent heat.
6. the meaning of relative humidity and its importance in everyday life.

8.1. INTRODUCTION :

The chapter is about heat. This is also a major branch of physics. We will look at some of the things heat can do, and see how we make use of heat in our everyday lives. We will ask the question "what is heat" ? and try to find an answer from the evidences. You will find suggestions for experiments ; try these out if you can. They will all work and they will help you to understand the important concepts and some physical effects of heat.

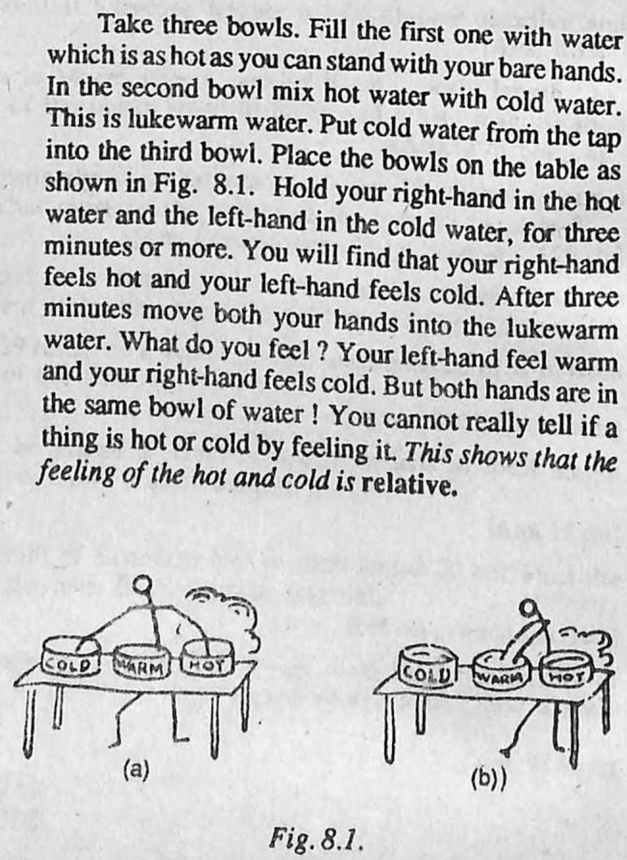
You will find many questions in this Chapter to stimulate you into thinking about heat. They will usually be easy, but if you have any difficulty try discussing them at home, or ask your teacher what he/she thinks.

Earlier heat was thought to be a kind of fluid (Caloric) but according to modern concept *Heat is a form of energy* known as **thermal energy.** A body has higher energy when it is hot than when it is cold. Its molecules absorb the heat and move about more vigorously at higher temperatures. In a gas, the molecules have sufficient kinetic energy in them so that each molecule moves about freely. What happens when we cool a gas below its condensation point? The kinetic energy of its molecules is reduced, while the attraction between molecules is increased. As a result the gas condenses into a liquid. What happens when we cool a liquid below its freezing point ? The energy of its molecules is further reduced, compared to the intermolecular forces of attraction. The liquid freezes into a solid. Thus, the energy of the molecules in a substance is low in the solid state, higher when it becomes a liquid and highest when it changes its state and becomes a gas. The attraction between the molecules holds the solidstate together. Heating a solid increases the energy of the molecules until at the melting point, the intermolecular forces are overcome to the extent that the solid liquifies and starts flowing. Further heating imparts more energy to the molecules of the liquid until at the boiling point, the kinetic energy of the molecules takes over and allows them to move quite independent of each other. In a gas thus, the attractive forces between the molecules is the least.

8.2. IDEA OF HOT AND COLD BODIES :

Let us do the following personal experiment on skin sense of hot and cold.

Take three bowls. Fill the first one with water which is as hot as you can stand with your bare hands. In the second bowl mix hot water with cold water. This is lukewarm water. Put cold water from the tap into the third bowl. Place the bowls on the table as shown in Fig. 8.1. Hold your right-hand in the hot water and the left-hand in the cold water, for three minutes or more. You will find that your right-hand feels hot and your left-hand feels cold. After three minutes move both your hands into the lukewarm water. What do you feel ? Your left-hand feel warm and your right-hand feels cold. But both hands are in the same bowl of water ! You cannot really tell if a thing is hot or cold by feeling it. *This shows that the feeling of the hot and cold is* **relative.**



(a) (b))

Fig. 8.1.

Fill a can with hot water. Put into it a pencil, a nail, a glass rod and a metal spoon. Feel the tops of these articles after two or three minutes. You will feel that the nail and the metal spoon are much hotter than the pencil and the glass rod (non-metals). This shows that the feeling of the hot and cold is not only relative but it depends upon the *nature of the body* we touch.

8.3. TEMPERATURE AND ITS MEASUREMENT :

We can use our skin to make rough guesses, but our sense of hot and cold is limited and unreliable. Our sense of touch can be used only to determine which of the two substances is at a higher temperature. It cannot be used if the two substances are almost at the same temperature, nor can it be used for very high and very low temperature. We, therefore, need a device which is independent of our sense of touch and which will measure the hotness or coldness of a body. Such a device is called a *thermometer*. A thermometer tells us just how hot or cold a thing is ; it can be used to compare different objects ; and it can be used again and again, to link up observations made on different days. It provides *definite* numbers, which form a *permanent, reproducible scale*—it has the characteristics of a good instrument. In passing from vague sensation to the definite scale of an instrument we are not just improving our incompetent skin's measuring system, we are inventing and putting into use a new concept : *temperature*. Our rough sense of hot and cold suggests the concept of temperature.

You can make your own thermometer at home using a bottle, plasticine, and thin plastic tubing [Fig. 8.2.]. Warm the bottle with your hands to drive out some air and get the water level at a suitable height.

Note how the level of the water varies as the temperature is varied. If you cool the bottle by pouring cold water over it, the water level in the tube will

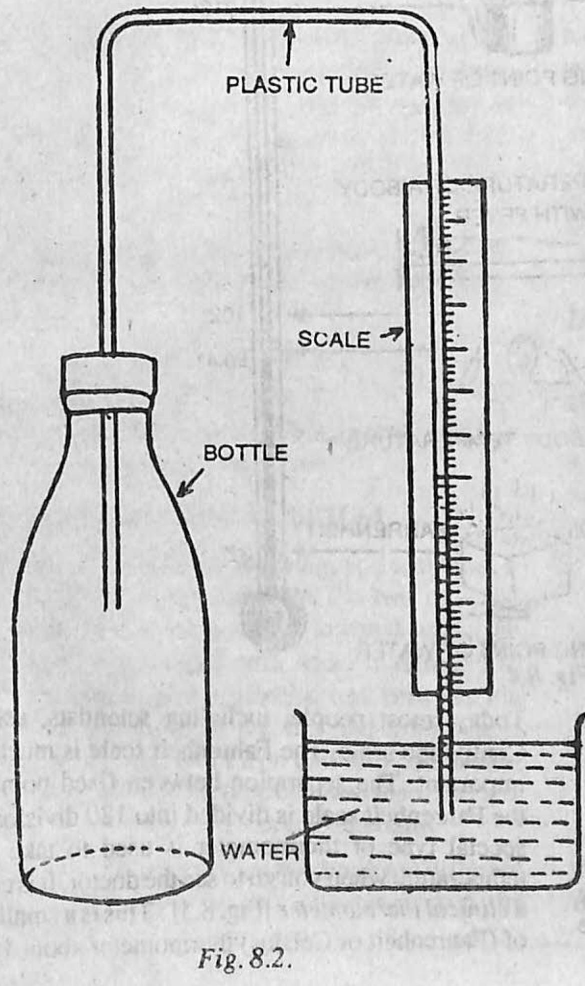


Fig. 8.2.

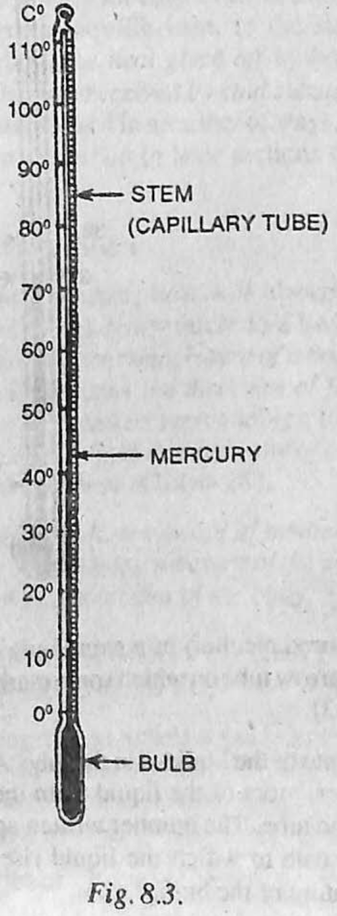


Fig. 8.3.

rise further. If you heat the bottle by bringing a candle flame near it, the water level in the tube will fall. The change in the level of water in the tube thus indicates the change in temperature. In the particular experiment, fall in the level of water in the tube indicates rise in temperature and rise in the level of water in the tube indicates fall in temperature.

Thus the temperature of a thing expresses and is a measure of its degree of hotness or coldness.

The above model of an air thermometer is similar to the one devised by Galileo in the sixteenth century. In fact he developed the first thermometer. Galileo noticed that gases expand on heating and contract on cooling. He utilised this property of the gases to build a thermometer.

There are different types of thermometers, but the most common type has a liquid (usually mercury or coloured alcohol) in a small bulb at the end of a long, narrow tube on which some marks are scratched [Fig. 8.3].

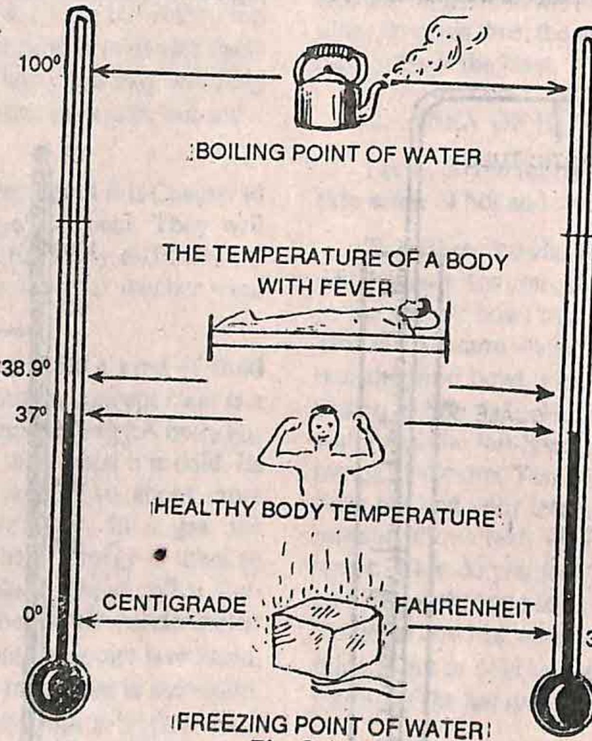


Fig. 8.4.

Some of the liquid is in the tube. As the temperature rises, more of the liquid from the bulb expands along the tube. The number written against the mark on the scale to which the liquid rises indicates the temperature of the bulb.

To get a standard scale of *markings* or *graduations* on a thermometer two *fixed points* must first be found. These points are temperatures which are easily obtained. The *upper fixed point* is the temperature of steam from boiling water. The *lower fixed point* is the temperature of melting ice. **On the Centigrade scale (°C)**, the difference between these two points is divided into 100 parts or degrees. The temperature of melting ice is 0°C and the temperature of steam from boiling water is 100°C. This scale is also called the **Celsius scale,** after a Swedish scientist.

On the *Fahrenheit scale* the ice point is 32°F (degree Fahrenheit) and the upper fixed point is 212° F [Fig. 8.4]. This scale came about because the two fixed points that the inventor, Fahrenheit, used were the temperature of the body, which he then thought was 96°F, and the temperature of a mixture of ice and salt which was 0°F. It has since been found that the temperature of a normal human body is 98.4°F. Today, most people, including scientists, use the Centigrade scale. The Fahrenheit scale is much less important. The separation between fixed points on the Fahrenheit scale is divided into 180 divisions. A special type of thermometer is used to take your temperature when you go to see the doctor. It is called a *clinical thermometer* [Fig. 8.5] : This is a small type of (Fahrenheit or Celsius) thermometer about 10 cm long. A healthy person has a temperature of 98.4°F (or 37°C). Any great deviation from this indicates illness. 105°F is regarded as very dangerous. To obtain the temperature of a patient the nurse usually places the thermometer under the tongue or in the armpit. This thermometer has a short, very thin capillary tube with a narrow portion (or constriction) at A. In expanding the mercury flows out of the bulb past the narrow portion, but when the thermometer is taken out of the patient's mouth or armpit the mercury does not flow back past the constriction. Thus the temperature can easily be recorded and read. To bring the mercury back into the bulb, the thermometer is shaken vigorously and the mercury is thus forced back through the constriction. This thermometer is graduated from 95° to 110°F or 35° to 42° C.

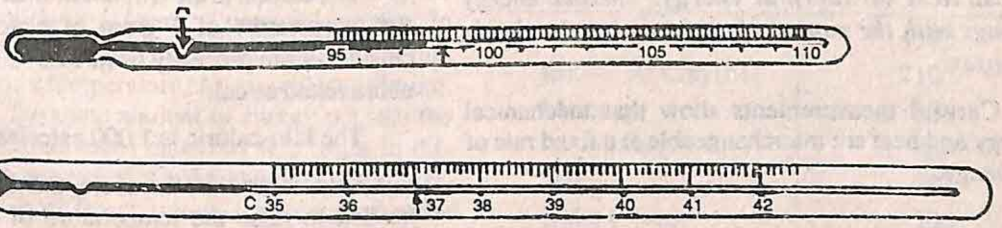


Fig. 8.5.

In order to convert the temperature on the Celcius scale to the Fahrenheit scale, we use the following relation :

$$\boxed{\frac{C}{100} = \frac{F-32}{180}}$$

where C is the reading on the Celsius scale and F is the reading on the Fahrenheit scale.

8.4. THERMAL EQUILIBRIUM

If water is too hot for washing, you may cool it quicky by adding cold water. As the two mix, the temperature of the hot water is lowered while the temperature of the added cold water is raised. The final temperature of the mixture lies between the original temperatures of the hot and cold water. Similarly if we drop a hot iron ball into cold water, soon the iron ball will become cold and the water and the iron ball will attain the same temperature.

Thus, it is clear that when two bodies at different temperatures come in contact with each other, the hotter body becomes cooler and the colder body becomes warmer till they attain the same temperature. Obviously, something is exchanged between a hot and a cold body during the time they are in contact and their temperature is changing. *That something which has been exchanging or transferred is called heat.* Each time two substances of unequal temperature are mixed, the warmer one loses heat and the cooler one gains heat until they both finally reach the same temperature. *No heat flows when the two bodies are at the same temperature.* The state when no heat flows from one body to another when they are brought in contact with each other is known as the state of **thermal equilibrium.** In the state of thermal equilibrium, *the heat given off by hot substances equals the heat received by cold substances.* This principle can be used in a variety of ways, some of which will be described in later sections of this chapter.

Definition of Temperature

As mentioned earlier, heat will always flow from a body at a higher temperature to a body at a lower temperature. Hence *temperature of a body is a property which determines the direction of flow of heat between the body and its surroundings.* In other words temperature indicates *thermal state of a body.* The SI unit of temperature is *kelvin* (K).

**According to modern concept of temperature, the temperature of a body is a measure of the average kinetic energy of the molecules of the body.*

8.5. THERMAL ENERGY (or HEAT AS A FORM OF ENERGY)

Sudden compression makes a gas hotter—gives it more heat—yet when we ask: "What does the moving piston do to the molecules"? the reply is : "It only makes them move faster". So *heat in a gas seems*

*** You will learn this definition in detail in higher classes.**

to be associated with molecular motion. Again, heat seems to appear when we hammer soft metal or rub rough surfaces. If you rub your hands together vigorously (try it now), your hands get warmed. Twist a pointed stick very quickly in a piece of wood [Fig. 8.6], it becomes hot and this would set the dry grass alight. A meteorite entering the earth's atmosphere, gets red hot due to friction with air and is completely vaporised before reaching the surface of the earth.

The above examples clearly illustrate that the mechanical energy (kinetic energy) of a body lost due to friction appears in another form of energy, which we call heat or thermal energy. *Thermal energy belongs with the motion of atoms and molecules in all cases.*

Careful measurements show that mechanical energy and heat are interchangeable at a fixed rate of exchange.

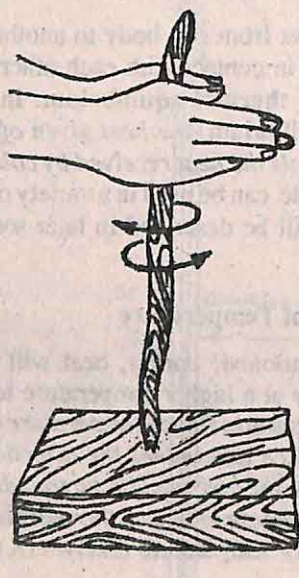


Fig. 8.6.

Anything that can do work is said to possess energy. If we can show, therefore, that heat can do work, such as making something move, then heat must be a form of energy. In fact, all evidences in our daily life indicate that heat is a form of energy known as thermal energy. For example, when water is boiled in a kettle with a loose lid, the steam forces its way out by pushing up the lid, which therefore moves up and down. Thus heat has caused motion.

You can think of many more ways in which themal energy (heat) can cause motion.

In ordinary talk, the word "heat" is used as a rough synonym for temperature ; but in science we use the two words for quite different things. We use the name heat for the essential stuff that makes a thing hotter ; temperature only shows how hot the thing is, how full of heat it is or the "pressure of heat" in it.

8.6. UNIT OF HEAT

Heat is measured in **calories**, more usually now, in **kilo-calories.**

The calorie is the amount of heat needed to raise the temperature of 1 gram of water by 1 degree celsius--more precisely from 14.5°C to 15.5 °C. It is abbreviated as cal.

The kilo-calorie is 1,000 calories.

Kilo-calorie is, therefore, the amount of heat needed to raise the temperature of 1 kilogram of water by 1 degree celsius. It is abbreviated as *Kcal.*

The **joule** (J) is the more usual unit of heat in SI system as heat is a form of energy.

8.7 MECHANICAL EQUIVALENT OF HEAT — (Mechanical Work and Heat)

The subject of heat had developed quite far in its practical sense well before its nature was known. Although we now recognize that heat is merely another form of energy, this was not realized until relatively late. As a result, heat units were defined as something quite distinct and having no direct relation to the defined units of energy. We could, of course, discard the old units, the calorie and kilo-calorie and express heat energy in joules. However, the calorie and kilo-calorie are well entrenched and are convenient to use. Hence, we continue to use them.

To find exactly how the defined unit of heat energy, the calorie is related to the defined unit of mechanical energy, the joule, one must resort to experiment. The first precise experiment to determine this correspondence was carried out by James Prescott Joule (1818-1889). One of the more accurate methods used was based on the conversion of potential energy to heat energy.

James Joule was the first to demonstrate that the ratio between work done or the energy lost in a mechanical process and the heat produced in the process is a constant. This constant is known as

mechanical equivalent of heat and it is represented by the symbol J. It is found that whatever be the nature of the substance or its volume, *4186 joules of mechanical work will always produce 1 kcal of heat.* In other words, we may write

$$\boxed{\begin{array}{c}\textbf{1 kcal = 4186 joules}\\ \textbf{or 1 cal = 4·186} \approx \textbf{4·2 joules}\end{array}}$$

This is the result accepted at present

8.8 SPECIFIC HEAT

When energy is absorbed by a material, part of the energy will contribute to further molecular motion, which is seen as an increase in temperature; and part of the energy may do work in expanding the material, which is a form of potential energy. In different materials, the fraction of the energy that contributes to a temperature change will be different. As a result, the same amount of energy put into the same mass of different materials will result in different temperature changes. Another way of expressing this is that different amounts of energy must be put into the same mass of different materials to cause the same temperature change.

For example, 4180 J put into 1 kg of water raises its temperature by $1^{o}C$ but only 880 J will raise the temperature of 1 kg of aluminium by $1^{o}C$.

The quantity of energy required to raise the temperature of 1 kg of a substance by $1^{o}C$ is called **specific heat** *of that substance.*

Specific heat of a substance is usually represented by the symbol C. In terms of joule, the unit of specific heat is *joule per kilogram degree celsius* (J/kg^{o}C). In terms of calorie, the unit of specific heat is *calorie per gram degree celsius* (cal/g^{o}C).

Hence, specific heat of water is $4180\ J\ Kg^{-1}\ {}^{0}C^{-1}$ = 1 cal/g^{0}C as 1 cal = 4.18 J.

What are the factors on which the quantity of heat required to heat a substance depends? In general, it has been found that the quantity of heat required to heat a substance depends upon (i) its mass, (ii) the rise in temperature, and (iii) nature of the substance.

If Q = heat required to raise the temperature of m kg of a substance of specific heat C through T^{o}C, then

$$\boxed{Q = C\,mT}$$

Reference is sometimes made to the **thermal capacity** of an object. *This refers to the amount of energy needed to raise the temperature of whole body by 1 C^{o}. It is equal to the product of its mass and the specific heat of its material.*

i.e., Thermal Capacity of an object
= mass of the object
× specific heat of the object = mC

Specific heats for a few common substances are listed in Table 8.1 below :

TABLE 8.1

SUBSTANCE	SPECIFIC HEAT (J/Kg °C)
Water	4180
Ice, — 10°C to 0°C	2100
Mercury	138
Aluminium	880
Steel	447
Glass (Flint)	500
Marble	900
Wood	1600
Iron	480
Brass	380
Copper	390
Gold	170
Silver	230
Lead	130
Paraffin	2140

8.9 PRINCIPLE OF CALORIMETRY (EQUILIBRIUM TEMPERATURE)

If two bodies at different temperatures be mixed together, they share heat with each other and finally attain an equilibrium (or common) temperature which lies between the temperatures of the two bodies. If it is assumed that there is no exchange of heat between the bodies and the surrounding objects and there is no chemical action between the constituents of the mixture, the hotter body loses as much heat as the colder body gains. In other words,

$$\boxed{\textbf{Heat lost = Heat gained}}$$

This is the principle used in the measurement of heat and is called the **principle of calorimetry** or **principle of mixtures.**

The vessel in which measurement of heat is usually carried on is known as *calorimeter* and is generally made of copper.

A large number of situations involving heat interchange can be elucidated by the application of the principle of calorimetry. In general, such situations involve the interchange of heat within an insulated vessel (a calorimeter), which effectively isolates the system from its surroundings. The above equation becomes clear in the light of the laws of conservation of energy.

We shall illustrate its use by the following example :

Consider two bodies A and B at temperatures T_A and T_B respectively. Let $T_A > T_B$. Let these bodies be brought in contact with each other. The body A will lose heat and the body B will gain heat. In other words the temperature of body A will fall and that of B will rise till the temperature of both the bodies becomes constant or equal. When this happens, we say that the two bodies have reached thermal equilibrium. The common constant temperature of both the bodies when they attain thermal equilibrium is known as *equilibrium temperature*. Let T_C be the equilibrium temperature in this case.

Let m_A be the mass of body A and C_A be its specific heat. Similarly let m_B be the mass of body B and C_B be its specific heat.

Heat energy lost by body A in cooling down from T_A to $T_C = C_A\, m_A\, (T_A - T_C)$

Heat energy gained by body B in raising its temperature from T_B to $T_C = C_B\, m_B\, (T_C - T_B)$

Since according to the principle of calorimetry,
Heat lost = Heat gained

$$\therefore C_A m_A (T_A - T_C) = C_B m_B (T_C - T_B)$$

$$\text{or } C_A m_A T_A - T C_A m_A T_C = C_B m_B T_C - C_B m_B T_B$$

$$\text{or } T_C = \frac{C_A m_A T_A + C_B m_B T_B}{C_A m_A + C_B m_B}$$

The above equation can be used to determine the equilibrium temperature T_C.

The above equation can also be used to determine the specific heat of a body as will be clear from the solved examples given at the end of this Chapter.

8.10 THERMAL EXPANSION OF SOLIDS

All solids expand on heating and contract on cooling, and they do these to different extents.

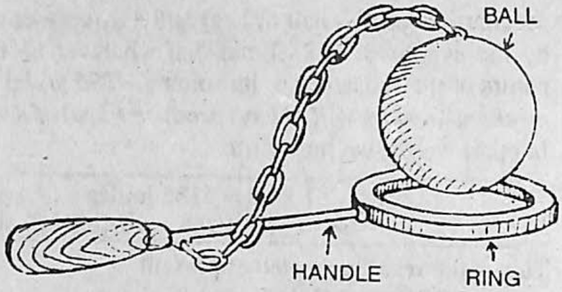


Fig. 8.7.

Ball and ring experiment : First try to pass the ball through the ring provided for it (Fig. 8.7). Put the ball in the flame for a few minutes. Remove it and try to pass it through the ring again. What happens ? Let the ball cool down and then try again. What happens? You will notice that when it is cold the ball passes through the ring, but when very hot it cannot pass through as it is now too big for it, *i.e.*, it has expanded.

It is clear from the above experiment that when a solid is heated it expands, and *this expansion takes place not in one direction only but in all directions.*

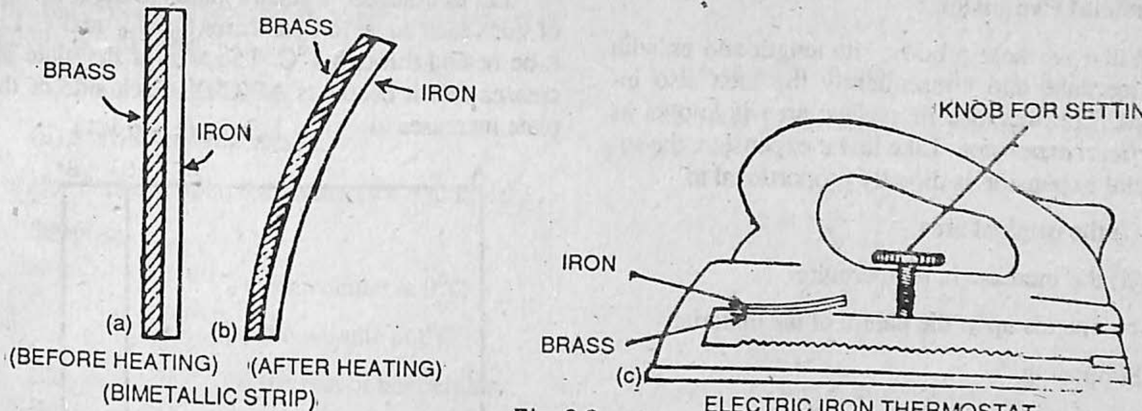
Now try the following experiment which illustrates further this phenomenon of expansion.

Take a compound bar (or bimetallic strip) consisting of two blades of two metals (*e.g.*, iron and brass) of equal length and equal thickness smoothly riveted together (Fig 8.8). First examine the compound bar and see that the blade is perfectly flat. Now put it in the flame for a few seconds. What happens ?

You will notice that the compound bar becomes bent. If the bar is a compound bar of iron and brass you will see that the bar is bent towards the iron side, as shown in Fig [8.8 (b)]. This can be explained by saying that brass expands more than the iron and that is why the compound bar is bent towards the iron side.

All solids expand on heating, but the extent to which they expand is different for different solids.

Bimetallic strips are most commonly used as reliable thermoswitches in automatic electric iron [Fig 8.8 (c)], refrigerators, temperature controlled ovens, toasters etc. The bending due to thermal expansion helps in breaking the circuit and controls the temperature of the iron while in use.



(BEFORE HEATING) (AFTER HEATING)
(BIMETALLIC STRIP)

ELECTRIC IRON THERMOSTAT

Fig. 8.8.

Types of Expansion :

When a solid is heated, it generally expands equally in all directions although the expansion is usually very small. This change in the dimensions of a body on heating results in the increase of length, area and volume of a body. The increase in length is called **Linear Expansion**. The increase in area is called **Superficial Expansion**. The increase in volume is called **Cubical Expansion.**

Linear Expansion :

When a thin metal rod is heated, its length increases and the increase varies directly as

(i) the rise in temperature and

(ii) the original length,

and also changes with the nature of the material.

If L_o be the length of the rod at 0°C and L_t its length at t°C, we have

$$L_t - L_0 \propto L_0$$
$$\propto t^oC$$

or $L_0t - L_0 \propto L_0t$

or $L_t - L_0 = \alpha L_0 t$ ... (i)

where α is a constant depending upon the nature of the material and is known as *Coefficient of Linear Expansion of the material*. Equation (i) gives the change in length. This relation gives us.

$$\alpha = \frac{L_t - L_0}{L_0 \, . \, t} \quad \text{... (ii)}$$

the definition of coefficient of linear expansion.

Coefficent of linear expansion is the increase in length per unit length at 0°C of a rod when its temperature is raised through 1°C.

Its unit is *per degree centigrade*. (per °C).

Equation (i) may be written as

$$L_t = L_o + L_o \alpha \ t$$

or $L_t = L_o (1 + \alpha \ t)$ ... (iii)

which gives us the final length.

Change in length $= L_t - L_0 = L_0 \alpha t$ ... (i)

Coefficient of linear expansion

$$= \alpha = \frac{L_t - L_0}{L_0 \, . \, t} \quad \text{.... (ii)}$$

Final length $= L_t = L_0(1 + \alpha t)$ ... (iii)

The coefficient of linear expansion of some common substances is given in the following table :

			per °C
Aluminium	...	...	0·0000255
Brass	...	...	0·0000187
Copper	...	...	0·0000167
Iron (cast)	...	...	0·0000106
Iron (wrought)	...	...	0·0000114
Iron (steel)	...	...	0·0000110
Platinum	...	...	0·0000090
Glass	...	...	0·0000090
Ice	...	...	0·000051
Hard rubber	...	...	0·000080
Porcelain	...	...	0·0000028
Zinc	...	...	0·000026
Nickel	...	...	0·0000128
Invar (alloy of Iron & Nickel)	...	...	0·00000009
Gold	...	...	0·000014
Silver	...	...	0·000019
Pyrex glass	...	...	0·000003

Superficial Expansion :

When we heat a body, its length and breadth both increase and consequently the area also increases. The increase in surface area is known as *superficial expansion*. Like linear expansion, the superficial expansion is directly proportional to

(i) the original area,

(ii) the increase in temperature

It also depends upon the nature of the material

Supposing

S_0 = the original area at °C

and S_t = the final area at t°C

$\therefore\ S_t - S_0$ = change in area.

Then we have

$$S_t - S_0 \propto S_0$$

$$\propto t$$

i.e., $S_t - S_0 \propto S_0 t$

or $S_t - S_0 = \beta S_0 t$ .. (i)

or $\beta = \dfrac{S_t - S_o}{S_o t}$ .. (ii)

where β is a constant depending upon the nature of the material and is known as *coefficient of superficial expansion*. Coefficient of Superficial Expansion may thus be defined *as the increase in area per unit area at 0°C when heated through 1°C.*

Relation (i) may be written as

$$S_t = S_0 + S_0\beta t$$

or $S_t = S_0(1 + \beta t)$ ... (iii)

which gives the final area.

These relations may be summarised here.

Coefficient of superficial expansion

$$= \beta = \frac{S_t - S_0}{S_0 t}$$

Increase in area $= S_t - S_0 = S_0 \beta t$

Final area $= S_t = S_0(1 + \beta t)$

* $\beta = 2\alpha$

It can be shown that the coefficient of superficial expansion is twice the coefficient of linear expansion.

Let us consider a square plate ABCD (Fig. 8.9) of sides each equal to L_0 and area $S_0 = L_0^2$ at 0°C. Let it be heated through 1°C. The area of the plate increases and it becomes AB′C′D′. Each side of the plate increases to $L_1 = L_0(1 + \alpha \times 1)$

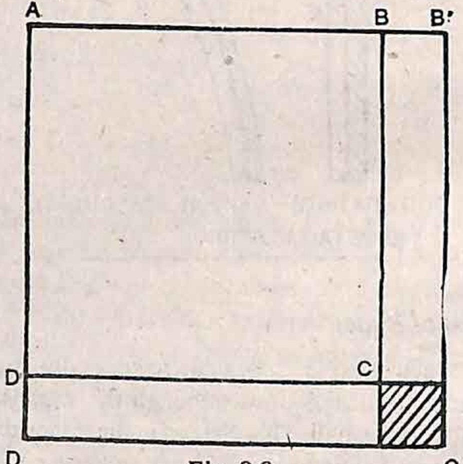


Fig. 8.9

The area AB′C′D′ is equal to

$$S_2 = L_1^2 = [L_0(1 + \alpha \times 1)]^2$$

$$\therefore \text{Change in area} = L_1^2 - L_0^2$$

$$= L_0^2(1 + \alpha)^2 - L_0^2$$

Hence coefficient of superficial expansion is given by

$$\beta = \frac{S_t - S_0}{S_0 \cdot t}$$

$$\therefore \quad \beta = \frac{L_0^2(1 + \alpha)^2 - L_0^2}{L_0^2 \times 1}$$

$$= (1 + \alpha)^2 - 1$$

$$= 1 + \alpha^2 + 2\alpha - 1$$

$$= \alpha^2 + 2\alpha$$

$$= 2\alpha$$

neglecting α^2 which is very small as compared with 2α.

Hence the coefficient of superficial expansion is twice the coefficient of linear expansion.

Cubical Expansion :

When a body is heated, its length, breadth and thickness all increase and consequently there is increase in volume. Like linear and superficial expansion, the increase in volume or cubical expansion is directly proportional to

(i) the original volume,

(ii) the rise in temperature.

It is also depends upon the nature of the material.

Suppose

V_0 = the volume at 0°C

V_t = the volume at t°C

and t = the rise of temperature,

then $V_t - V_0 \propto V_0$

$\propto t$

i.e., $V_t - V_0 \propto V_0 t$

or $V_t - V_0 = \gamma V_0 t$ ... (i)

or $\gamma = \dfrac{V_t - V_0}{V_0 t}$ ... (ii)

where γ is a constant whose value depends upon the nature of the material and is known as *coefficient of cubical expansion*.

Coefficient of cubical expansion may thus be defined as *the increase in volume per unit volume at 0°C produced by 1°C rise of temperature.*

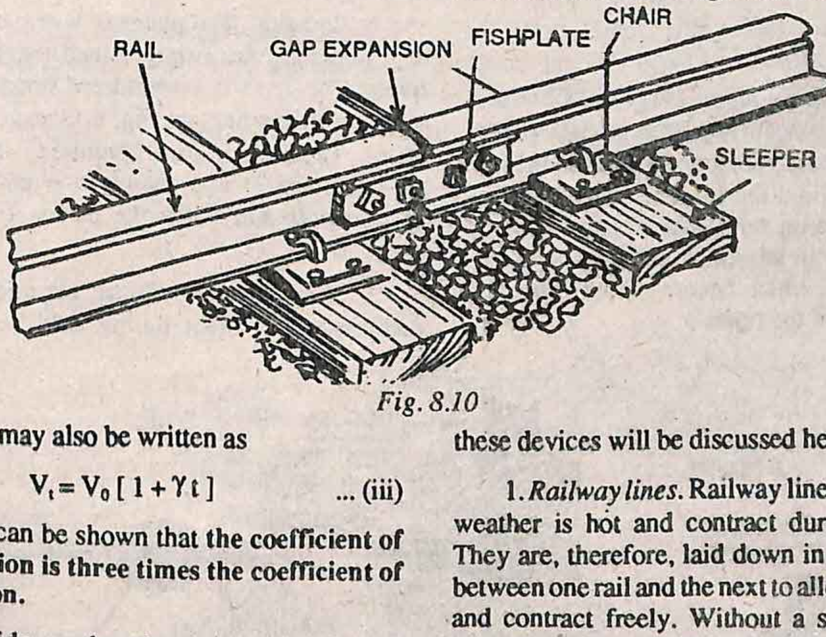


Fig. 8.10

The eq. (i) may also be written as

$$V_t = V_0 [1 + \gamma t] \quad \text{... (iii)}$$

$\gamma = 3\alpha$. **It can be shown that the coefficient of cubical expansion is three times the coefficient of linear expansion.**

Let us consider a cube whose each side is L_0 and volume L_0^3 at 0°C. Let it be heated through 1°C, so that each side increases to $L_1 = L_0 (1 + \alpha \times 1)$ and the volume $V_0 = L_0^3$ at 0°C increases to V_1 given by

$$V_1 = L_0^3 (1 + \alpha)^3$$

$\therefore$ Increase in volume $= L_0^3 (1 + \alpha)^3 - L_0^3$

Therefore coefficient of cubical expansion is given by

$$\gamma = \frac{V_1 - V_0}{V_0 \cdot t}$$

$$= \frac{L_0^2 (1+\alpha)^3 - L_0^3}{L_0^3 \times 1}$$

$$= (1 + \alpha)^3 - 1$$

$$= 1 + 3\alpha + 3\alpha^2 + \alpha^3 - 1$$

$$= 3\alpha + 3\alpha^2 + \alpha^3$$

$$= 3\alpha$$

because $3\alpha^2$ and α^3 are very small as compared with 3α and hence are neglected.

Hence the coefficient of cubical expansion is three times the coefficient of linear expansion.

A FEW APPLICATIONS OF THE EFFECTS OF EXPANSION OF SOLIDS :

In our everyday experience we find that the expansion and contraction of substances sometimes cause us trouble or even danger and so we have to devise ways of avoiding these difficulties. A few of these devices will be discussed here.

1. *Railway lines*. Railway lines expand when the weather is hot and contract during cold weather. They are, therefore, laid down in lengths with gaps between one rail and the next to allow them to expand and contract freely. Without a space between the rails, the joints would swell up in hot weather as a result of expansion, and the train would be derailed.

The rails are connected by fishplates. These have oval holes for the bolts so that movement to and fro is possible when expansion or contraction takes place. The rails rest on steel "chairs", as shown in the diagram (Fig 8.10). Between the rail and the chairs are wooden wedges which keep the rail in position. These wooden wedges are sufficiently soft to allow the rail to expand sideways.

These days, in some countries and also partly in India, the railways are using welded rails with single rail length of a few kilometres. Two such rails are joined in a wedge, so that when rails expand, they slide past each other (Fig. 8.11).

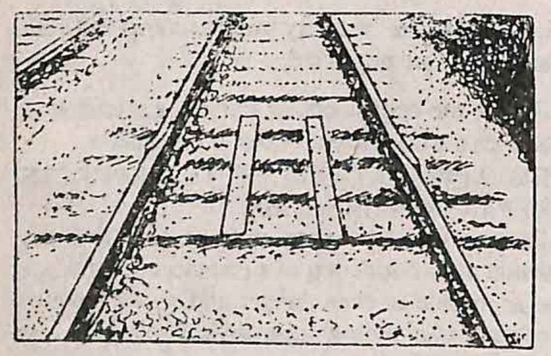


Fig. 8.11

2. *Expansion loops in pipes.* In several factories and workshops where steam is passed through pipes the steam pipes are fitted with loops, as shown in Fig. 8.12. These loops allow the pipe to expand easily when hot steam is passing through and contract when it cools down. Without the loops, the pipes tend to expand at the joints, which become loose, causing leakage or bursting of the pipes.

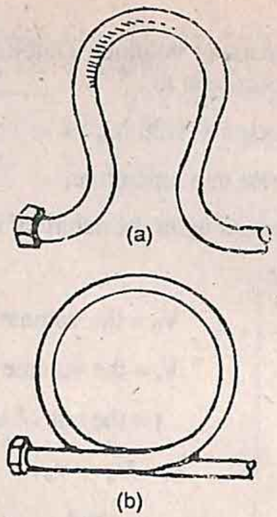


Fig. 8.12 Steampipe expansion loops

We can show experimentally that the force of expansion is very great. All substances exert great forces if one tries to stop them expanding or contracting. These forces are often used to tighten some things and to push others.

3. *Locomotive wheels.* Locomotive wheels are fitted with iron tyres. These tyres are made a little smaller than the wheels. They are first heated until red hot, during which they expand and can easily be slipped on to the wheels. On cooling they contract and grip the wheels firmly.

4. *Riveting.* The plates of a ship and the sheets of a boiler can be firmly joined together by using rivets. The rivet is inserted red hot through holes opposite each other (see Fig. 8.13 stage 1) in the two plates. The rivet is now hammered flat while still red-hot (stage 2) and then left to cool. As it cools it contracts and binds the plates firmly together (stage 3).

5. *Steel bridges.* These expand during hot weather and contract during cold weather. If the

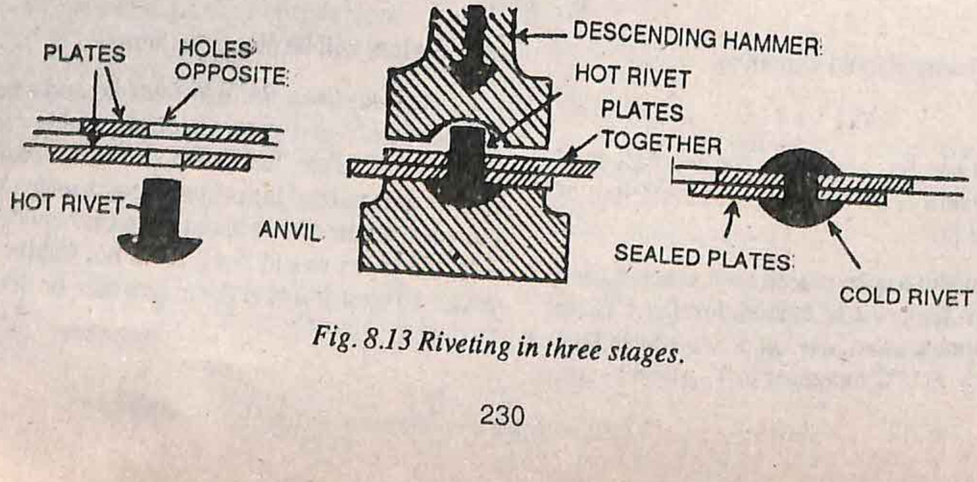
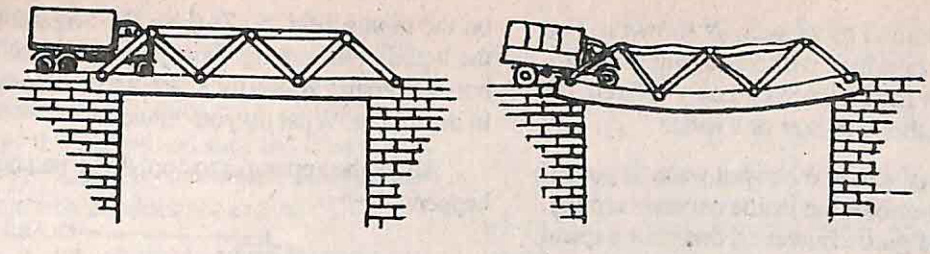
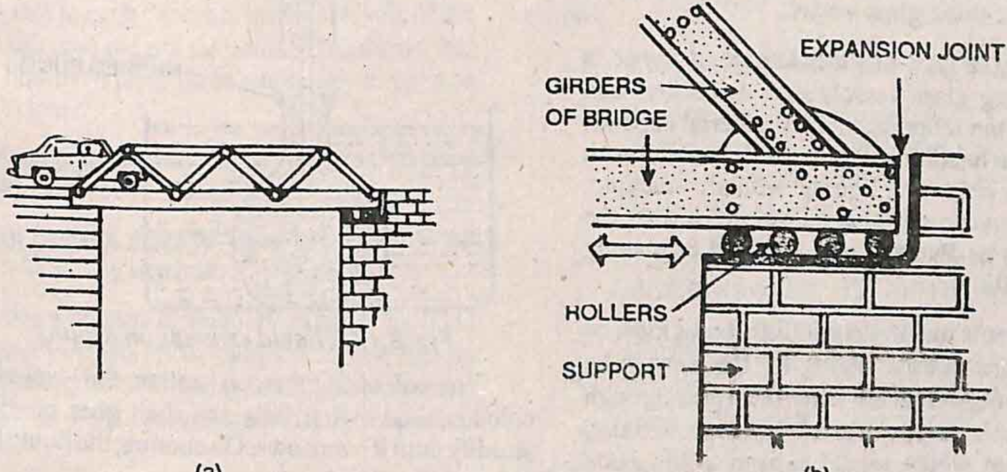


Fig. 8.13 Riveting in three stages.



(a) BEFORE EXPANSION (b) AFTER EXPANSION

Fig. 8.14 Expansion of a bridge in hot weather



(a) (b)

Fig. 8.15 A roller bearing

bridge is fixed at both ends, as shown in Fig. 8.14 (a), you can well imagine what will happen in hot weather [see Fig 8.14 (b)].

To avoid this, long steel bridges are built so that the ends of the steel structures rest on rollers which allow the bridge to expand or contract without weakening the structure Fig 8.15.

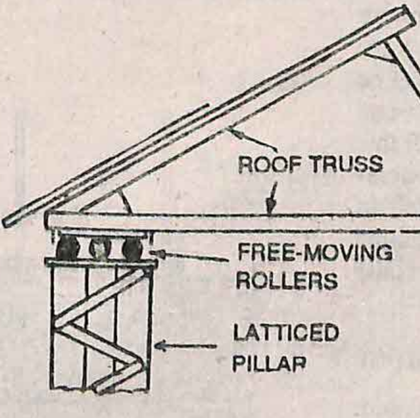


Fig. 8.16 A steel-framed roof showing roller arrangements

Large steel-framed roofs such as shown in Fig. 8.16 expand and contract with changing temperatures, and, to allow for this, one end only is fixed, the other resting on either a rocker or a roller.

6. *Expansion of glass*. When hot water is poured into a thick glass tumbler the inside expands rapidly. The outside of the glass, however, does not expand at the same rate, because the heat takes some time to pass through the glass (it is a poor conductor of heat). The result is that a strain is produced in the glass which makes it crack ; and so take care never to pour hot water into a thick glass vessel.

Nowadays, a type of glass known as *Pyrex* is used for making glass vessels such as beakers and flasks used in the laboratory. This material expands only slightly on heating, and so vessels made of such materials can hold hot liquids without cracking. *Vitreosil* and *quartz* are other substances having the same property as Pyrex. They are used in making cooking utensils.

The filaments inside electric-light bulbs must be connected to the outside wiring for the lamp to be used, and this means that the wires must pass through the glass. For this purpose a substance must be found for the filament which would expand to the same extent as glass to prevent cracking from unequal expansion. Platinum may be used, but it is expensive. An alloy of nickel and steel (45% nickel) has been found suitable which expands at the same rate as glass. It is known as *platinite*.

7. *Compensated pendulums*. The time kept by the swinging of a pendulum depends on the length of the pendulum. If, therefore, the pendulum wire expands or contracts owing to changes in temperature it is clear that the pendulum will not always keep correct time. There are devices whereby this can be remedied. For instance, a metal known as *invar* can be used for making the pendulum. The length of this metal changes very little with changes in temperature. In fact, it will require a large rise or fall in temperature to change its length to any appreciable extent. Other methods are used, and you will come across these in higher classes.

8.11 EXPANSION OF LIQUIDS (FLUIDS)

Fill the flask to the brim with the coloured liquid. Fit in the rubber bung so that a good length of the glass tubing is outside the flask. Add a bit of the coloured liquid until the length of the liquid shows in the glass tubing. With the aid of a paper scale fixed on the tubing (Fig. 8.17) mark the original level of the liquid in the tubing. Now place the flask inside a hot-water bath. Watch the level of the coloured liquid in the tubing. What do you notice ?

Allow the apparatus to cool down and note what happens.

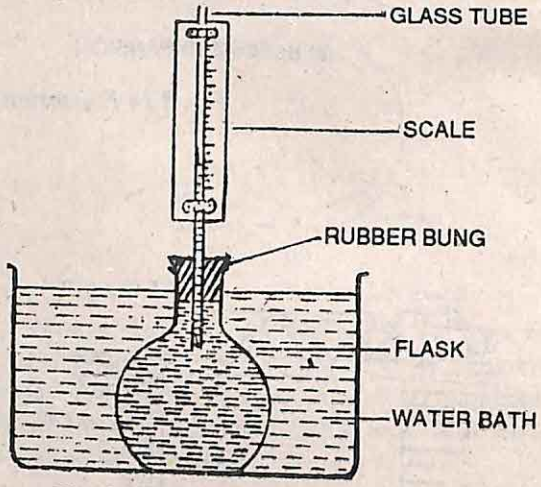


Fig. 8.17 A liquid expands on heating

You will notice that, on heating, the level of the coloured liquid first falls and then goes on rising steadily until it overflows. On cooling, the liquid falls to its original level.

The level of the liquid first falls, because the glass flask, being first affected by the heat, expands, providing more space for the liquid. The continuous rise of the liquid that follows shows that the liquid is expanding as it also is being heated.

The fall in the level when the apparatus is cooled shows that the liquid contracts on cooling.

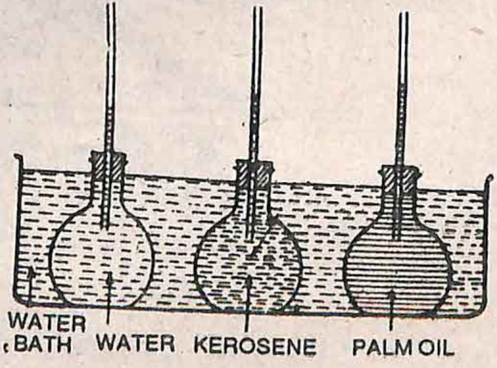


Fig. 8.18 Comparison of expansion of different liquids.

Take three flasks. Fix each flask as described in the last experiment and arrange them as shown in the diagram (Fig. 8.18). One flask contains water, another kerosene and the third palm oil. Mark the initial levels of the liquids and then the final levels, after they have remained for a few minutes in a water bath whose temperature does not exceed 65°C.

(Why is it not advisable to go beyond this temperature ?)

You will notice the original fall in the level of each liquid and the continuous rise that follows it. There is a rise in each case, but the final levels of the liquids in the tube are not the same. This shows that while all liquids expand on heating, they expand to different extents.

Try to arrange the three liquids used in the above experiment in the order of their expansion.

Below is given a list of liquids in order of the extent to which they expand.

Suppose a volume of mercury expands by IC.C when heated through 50°C, then the same volumes of the following liquids will expand by the amounts shown against them when heated through the same temperature :

Alcohol	6.0 cc approximately
Turpentine	4.8 cc approximately
Kerosene	4.4 cc approximately

It must be noted that for the same rise in temperature, liquids expand more than solids.

If V_1 is the volume of a given mass of a liquid at temperature T_1 and if V_2 is its volume at temperature T_2.

We have,

Change in volume = $V_2 - V_1 = V_1 \gamma (T_2 - T_1)$

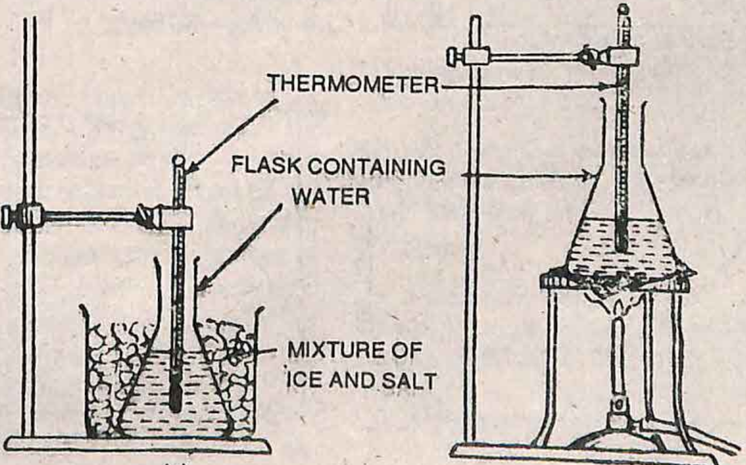
where γ is the coefficient of cubical expansion of the liquid.

Thermal expansion of mercury is utilized in making thermometers. Mercury has the following distinct advantages over all other liquids for this purpose :

1. It can be seen easily through glass.
2. It does not wet its container, *i.e.*, when mercury rises to a level in the tube and then falls to a lower level it does not leave drops on the tube as water does.
3. It can be used for a large range of temperatures, as it melts at –39°C and boils at 357°C.
4. Its expansion is uniform.
5. It quickly assumes the temperature of anything with which it is in contact.

8.12 CHANGE OF STATE

You have learnt that matter exists in three states, namely, solid, liquid and gas. You have also learnt that matter can be changed from one state into another. The following experiments illustrate what happens as one state is changed into another.



(a)

(b)

Fig. 8.19 Apparatus to demonstrate the existence of latent heat.

(a) Place the first conical flask inside the vessel containing the mixture of ice and salt and erect a thermometer vertically in the flask [Fig.8.19 (a)]. Take the temperature at one–minute intervals until the temperature reaches about –3° C. Draw a graph of *temperature* along the y–axis against *time* along the x– axis.

Record what you notice about the water.

(b) Weigh the second flask with some water in it. Place it on the bunsen flame [Fig 8.19 (b)] and start taking the temperatures at intervals of one minute until the water has boiled for five minutes. Draw a graph in the same way as in (a) above.

(c) Now cool the flask and weigh it again with the water inside. Record your readings and your observations in the following manner :

Time (min)	(a) Temperature (°C) of water being cooled	(b) Temperature (°C) of water being heated

Weight of beaker + water before heating = g
Weight of beaker + water after heating = g
Loss in weight of water = g

You will observe that in (a) :

(i) as the water is cooled, the temperature goes down along a smooth curve to 0°C, where it remains the same for a long time before it starts going below 0°C [see Fig. 8.20 (a)] ;

(ii) at the end of the experiment the water has turned to ice.

Notice that in (b) :

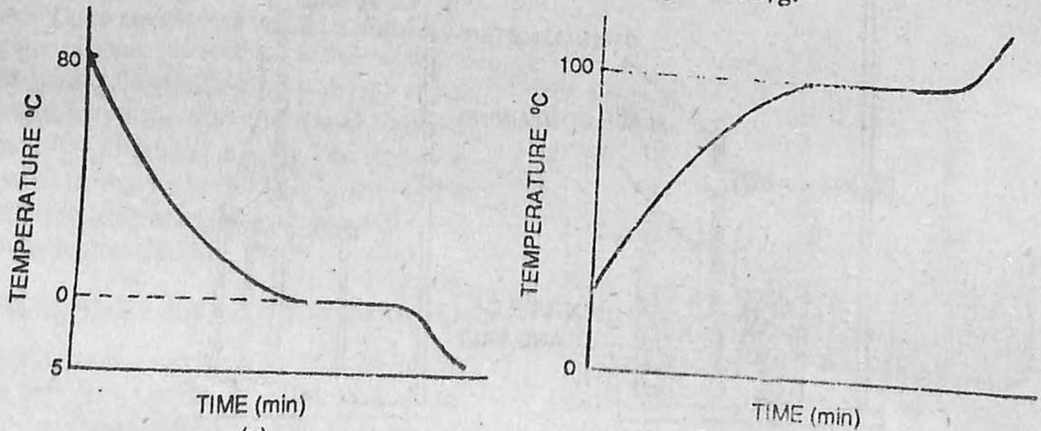
(i) the temperature rises uniformly along a smooth curve until it gets to around 100°C, where it remains without rising any further [see Fig. 8.20 (b)].

(ii) the wight of the water at the end of the experiment is less than it was before heating started.

Explanation : (a) The temperature of the water remains at 0°C, during the period that the water is changing from water into ice and does not go below 0°C, until all the water has frozen. During the process heat is being lost from the water, but the thermometer does not show this. Such heat is 'invisible' heat and is known as *latent heat of fusion of ice*. When any liquid changes from liquid to solid it is said to be losing its latent heat of fusion and there is no change of temperature during the period of change.

The quantity of heat required to completely change 1 kg of a solid to liquid at its melting point, without any change in temperature, is known as latent heat of **melting** or **latent heat of fusion of the solid.**

To change 1 kg of ice at 0°C to 1 kg of water, still at 0oC requires 334×10^3 J or 334 kJ. To change 1 kg of water at 0°C to 1 kg of ice at 0°C, 334 kJ must be removed. The latent heat of fusion of water is 334 kJ/kg ≈ 80 cal/g.



(a) (b)

Fig. 8.20 (Graph to show the existence of latent heat)

(b) The temperature of the water remains at about 100°C during the period that the water is changing from water into steam and does not rise beyond it until all the water has changed into steam. Heat is being given to the water during the process, but the thermometer does not show it. This again is 'invisible' heat and is called *latent heat of vaporisation of water*. When any liquid changes from liquid into gas it is said to be absorbing latent heat of vaporisation and there is no change of temperature during the process.

Each kilogram of water vaporized requires 2.26 million joules. When water vapour condenses, a corresponding amount of energy, 2.26 million joules per kilogram, must be given to the surroundings. The **latent heat of vaporization of water** *is the quantity of heat required to completely change 1 kg of water to water vapour at its boiling point (100°C), without any change in temperature.*

Its value is 2260 kJ/kg at the boiling point.

(c) In the second experiment some of the water has changed into steam, hence the weight of the water after heating is less than it was before heating.

The temperature at which a solid changes into a liquid is know as the *melting point* of the substance, and the temperature at which a liquid changes into a gas is known as the *boiling point* of that substance. Certain substances such as water and several salts have sharp boiling and melting points, and they are even identified by these values, while others, such as candle wax, do not have such a definite melting point.

If L denotes the latent heat of a substance of mass m then it will need mL heat for its complete change of state.

The latent heats play an important part in the weather on earth. Large bodies of water not only have a large capacity for heat storage, as they vaporize during hot weather, there is a cooling effect on the surroundings. In cool weather, freezing is slowed because of the necessity to remove the latent heat of fusion. Both processes have a stabilizing effect on the temperature in the surrounding area. Also, when water vapour condenses to form a mist, the latent heat goes to the surroundings and a slight warming effect can be noted. Similarly, the latent heat of fusion is released when snowflakes are formed, and a noticeable warming occurs just before snow falls on an otherwise cold winter day.

The large amount of energy released when steam condenses also explains why burns caused by steam are often much more severe than burns caused by even boiling water.

The human body continually produces heat ; even in the resting state the average person produces heat at a rate of about 90 J/s. When you are using energy to do work, even more heat is produced. This heat must somehow be carried to the environment. In dogs, which do not have glands for sweating and often have too thick a coat to allow sufficent heat transfer to the surroundings ; the principal method of heat loss is through breathing. The dog pants in order to increase the amount of exhaled vapour and hence the rate of heat loss.

*Can a liquid turn into a gas without boiling ?

If you weigh a beaker of water and leave it on the table overnight, then re-weigh it the following morning, you will notice a loss in weight showing that some of the water has escaped into the air during the night. This change of water into vapour without the application of heat to it is known as *evaporation*. This is well illustrated when you leave damp clothes spread out in the air to dry. In the same way, the waters of the oceans, lakes and rivers evaporate slowly *at all temperatures*.

The rate of evaporation depends on several factors :

1. *The area of the surface exposed.* A wet piece of cloth would dry much more quickly if spread out than if left folded. A large surface area aids evaporation.

2. *The temperature of the liquid.* A wet piece of cloth dries much more quickly on a hot, sunny day than on a cold, wet one.

3. *The wind.* A wet piece of cloth would dry much more quickly on a windy day than on a calm day. The wind helps to remove the vapour as it is formed.

4. *The dryness of the atmosphere.* When the atmosphere is laden with moisture, the rate of evaporation decreases ; but when it is dry the rate of evaporation is quickened. Hence wet clothes dry more quickly in dry air than in damp air.

5. *The nature of the liquid.* If you place equal

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* For further knowledge only.

quantities of ether, alcohol, petrol, water and palm oil in identical vessels exposing equal areas of their surfaces to the air you will find that they will evaporate at different rates, the ether having the highest rate of evaporation. Thus, different liquids evaporate at different rates.

***Evaporation produces cooling**

Try the following experiment :

Make a small pool of water on a matchbox. Stand on it a beaker containing some ether. Using a glass tube, blow some air through the ether (Fig. 8.21). Continue to blow until all the ether has evaporated. Touch the sides of the beaker. Also try to lift up the beaker. What do you notice ?

You will observe that the sides of the beaker will grow cold and wet within a few seconds. You will also see that when you try to lift the beaker the match-box comes up with it.

As air is blown through the ether, the ether evaporates very quickly. In evaporating (*i.e.*, changing from liquid into vapour) it absorbs *latent heat* of vaporisation from the surrounding air and from the water underneath the beaker. Thus, the water vapour in the air condenses on the side of the beaker and the water underneath it gets so cold that it freezes (*i.e.*, it turns into ice). This makes the beaker stick on to the match-box and it becomes difficult to separate them.

Using the Molecular Theory of Matter we can say that the faster molecules on the surface are able to escape from the attraction of the molecules below them and so turn into vapour, leaving the slower molecules behind. And since the temperature of a body is a measure of the rate of movement of the

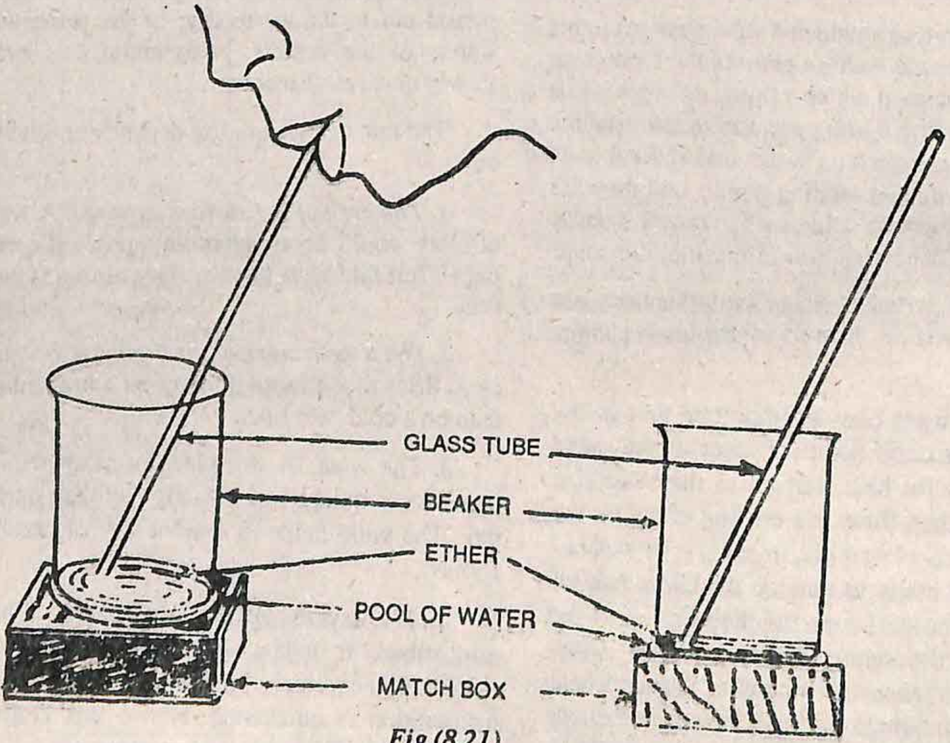

Fig (8.21)
(Evaporation causes cooling)

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* For further knowledge only.

molecules, it is therefore clear that the liquid left behind, consisting of slower-moving molecules, would be cooler. Thus, evaporation causes cooling.

There are numerous practical applications in everyday life based on the phenomenon that evaporation causes cooling. Some are mentioned below :

(i) Water in an earthen pot or *surahi* becomes cooler because an erthen pot has a large number of extremely small pores. Water comes out through them and evaporates from the surfaces, cooling the whole system. The latent heat required for evaporation is taken from the water in the earthen pot.

(ii) During summer, we perspire and evaporation of perspiration helps to cool our bodies.

(iii) Evaporation of water from the trees keeps them cool during summer months.

8.13 RELATIVE HUMIDITY

Evaporation is continuously taking place from the surface of water of the ponds, lakes, the rivers and the sea and millions of tons of water is drawn up into the atmosphere in the form of vapours every minute. So a very large quantity of water is in the atmosphere in the form of vapours. The presence of water vapours can be shown by putting pounded ice in a tumbler. Soon it is noticed that the water vapours get condensed on the outer surface of the tumbler.

The amount of water vapours present in the atmosphere is not a constant quantity but it is different at different places and at a particular place also it is different at different times. It depends upon the local conditions prevailing at a place. *The actual amount of water vapours present in 1* m^3 *of the atmosphere is called the absolute humidity.*

The absolute humidity is of no use to us because it is just possible that the actual amount of the vapours present in the atmosphere on a summer day may be greater than the amount of the vapours present on a winter day and the former would be drier than the latter. So the knowledge of absolute humidity is not sufficient to find out the dryness or dampness of atmosphere. Thus to know the exact condition of dryness or dampness of the atmosphere we should know (i) the amount of water vapours actually present in the air, and (ii) the amount of water vapours required to saturate it at the same temperature. The ratio between the two is called **Relative Humidity.**

The **Relative Humidity** *is defined as the ratio of the actual amount of water vapours present in a certain volume of air to the amount of water vapours required to saturate the same volume at the same temperature.*

Relative Humidity =

$$\frac{\text{Amount of water vapours in a certain volume (v) of air}}{\text{Amount of water vapours required to saturate the same volume (v) at the same temperature.}}$$

If at a given temperature a metre cube of air holds m kg of water vapour when it could hold m_s kg on saturation, then

$$\text{Relative Humidity (R.H.)} = \frac{m}{m_s} \times 100\%$$

It is clear that R.H. is less than one so we generally multiply the ratio with 100 and express it as *percentage humidity*.

If R.H. is high, we feel sultry, clothes do not dry easily. Temperatures between 22°C and 25°C with a R.H. value of about 50% are considered comfortable.

The process of regulating the temperature humidity, purity and circulation of air is called *air conditioning*.

SOLVED EXAMPLES

Example 1.

Convert -273°C to Fahrenheit scale.

Solution :

$$\text{Now,} \quad \frac{F-32}{180} = \frac{C}{100}$$

where F is the reading on the Fahrenheit scale and C is the reading on the Celsius scale.

$$\therefore \quad \frac{F-32}{180} = \frac{-273}{100}$$

$$\text{or} \quad F = -459.4^\circ F$$

Example 2.

Convert 98.4° F into °C.

Solution :

$$\frac{F-32}{180}=\frac{C}{100}$$

$$\therefore \quad \frac{98.4-32}{180}=\frac{C}{100}$$

or $C = 36.8^\circ C$

Example 3

At what temperature does the Fahrenheit scale show the same reading as the Celsius scale ?

Solution :

Let $F = x = C$

Now $\dfrac{F-32}{180}=\dfrac{C}{100}$

$$\frac{x-32}{180}=\frac{x}{100}$$

or $x = -40^\circ F = -40^\circ C$

Example 4.

A bar 0.5 metre long is heated from 14°C to 98°C. If the increase in length is 0.7 mm, find the coefficient of linear expansion.

Solution :

Here, $L_{14} = 0.5$ m

Increase in length = 0.7 mm = 0.0007 m

Rise in temperature = 98–14 = 84°C

$\alpha = ?$

Now coefficient of linear expansion α

$$=\frac{\text{Increase in length}}{\text{Original length} \times \text{rise in temp.}}$$

$$=\frac{0\cdot0007}{0\cdot5\times84}$$

$$= \mathbf{0.000017/^\circ C}$$

Example 5.

A scale made of iron is exactly a metre in length at 20°C. What will be its length at 40°C ? Coefficient of linear expansion of iron is 12×10^{-6} per °C.

Solution :

Here, $L_{20} = 1\text{m}$

$\alpha = 12\times10^{-6}$ per °C

Rise in temperature = $t = 40 - 20 = 20^\circ C$

$L_{40} = ?$

Now,

$$L_{40} = L_{20}[1 + \alpha(40-20)]$$

$$\therefore \quad L_{40} = 1\,[\,1 + 12\times10^{-6}\times20]$$

$$= 1\,[1 + 2.4\times10^{-4}\,]$$

$$= \mathbf{1.00024\ m}$$

Hence the length of the iron scale at 40°C will be 1.00024 m.

Example 6.

Calculate the energy required to heat 1 kg of water from 20°C to 100°C. Specific heat of water is 4180 J/kg °C.

Solution :

Here, $m = 1$ kg

$C = 4180$ J/kg °C

$T = (100–20) = 80^\circ C$

$Q = ?$

Since $Q = CmT$

$\therefore \quad Q = 4180\times1\times80$ J

$= 334400$ J

$= \mathbf{3.344\times10^5\ J.}$

Example 7.

When 0.2 kg of brass at 100°C is dropped into 0.5 kg of water at 20°C, the resulting temperature is 23°C. Find the specific heat of brass. Specific heat of water is 4200 J/kg °C.

Also determine the thermal capacity of brass.

Solution :

Here, mass of brass = $m_1 = 0.2$ kg

Temperature of brass = $T_1 = 100^\circ C$

Mass of water = $m_2 = 0.5$ kg

Temperature of water = $T_2 = 20^\circ C$

Resulting temperature = $T_C = 23^\circ C$

Specific heat of water = $C_2 = 4200$ J/kg°C

Let specific heat of brass = $C_1 = ?$

Heat lost by brass = $m_1C_1(T_1 - T_C)$

$$= 0.2\ C_1\ (100 - 23)$$

$$= 0.2 \times 77C_1$$

Heat gained by water = $m_2\ C_2\ (T_C - T_2)$

$$= 0.5 \times 4200\ (23 - 20)$$

$$= 0.5 \times 4200 \times 3$$

According to the principle of calorimetry,

Heat lost = Heat gained

or $0.2 \times 77 \times C_1 = 0.5 \times 4200 \times 3$

$$\therefore\ C_1 = \frac{0.5 \times 4200 \times 3}{0.2 \times 77}\ \text{J/kg}^\circ\text{C}$$

$$= 0.41 \times 10^3\ \text{J/kg}^\circ\text{C}$$

Thermal capacity of brass = m_1C_1

$$= \mathbf{0.082 \times 10^3\ J.}$$

Example 8.

When 500 g boiling water is poured into a mug which weighs 0.15 kg, the temperature of water falls to 70°C. If the specific heat of the substance of the mug is 0.8×10^3 J/kg°C, calculate the amount of heat lost by water. Specific heat of water = 4200 J/kg°C.

Solution :

mass of boiling water = m_1 = 500 g = 0.2 kg

mass of mug = m_2 = 0.15 kg

T = Fall in temperature of the boiling water = 70°C

C_2 = Specific heat of mug = 0.8×10^3 J/kg°C

C_1 = Specific heat of water = 4200 J/kg°C

Heat lost by water = ?

Now, Heat lost by water = Cm_1T

$$= 4200 \times 0.2 \times 70\ \text{J}$$

$$= 58800\ \text{J}$$

$$= \mathbf{5.88 \times 10^4\ J.}$$

Example 9.

How many joules are required to change 2 kg of ice at 0°C to water at 0°C ? Latent heat of fusion of ice = 334 kJ/kg.

Solution :

Here, mass of ice = m = 2 kg

Latent heat of fusion of ice = L = 334 kJ/kg

Q = ?

Since Q = mL

$\therefore$ Q = 2 × 334

= **668 kJ.**

Example 10.

Air at 25°C has a relative humidity of 75%. A metre cube of air holds 17.6 g of water, how much amount of water vapour could it hold on saturation.

Solution :

Here, R. H. = 75%

m = 17.6 g

m_s = ?

Since $\text{R. H.} = \frac{m}{m_s} \times 100\%$

$$\therefore\ 75 = \frac{17{\cdot}6}{m_s} \times 100$$

or $m_s = \frac{17{\cdot}6}{75} \times 100 = \mathbf{23.7\ g.}$

SUMMARY

1. The sensation of hotness or coldness is not only relative but it also depends upon the nature of the body we touch.
2. The thermal energy (or heat energy) of a material is the mechanical energy (potential and the kinetic energy) of its particles that can be evolved as heat.
3. Thermal energy which is being taken up by a material, being given up by a material, or being transferred from one material to another is heat.
4. The temperature of a body is a measure of its ability to give up heat to, or absorb heat from, other bodies. It is thus a property which governs the flow of heat. It expresses the degree of hotness or coldness possessed by a body.

5. Calorie, kilo-calorie and joule are the various units of heat. **In S.I. system, heat is measured in joules.**

6. Specific heat of a substance is the thermal energy required to heat 1 g of a substance through 1°C. The unit of specific heat is cal 1/g °C.

   In terms of joule, specific heat of a substance is defined as the quantity of heat (in joule) required to raise the temperature of 1 kg of the substance through 1 °C. In this case, its unit is J/kg °C.

7. 4186 joule of mechanical work will always produce 1 kcal of heat. The ratio $\frac{4186}{1\text{ kcal}} = J$, mechanical equivalent of heat

   1 kcal = 4186 joule

   or 1 cal = 4.186 joule ≈ 4.2 joule

8. The amount of heat gained or lost by a substance is given by

$$Q = CmT$$

9. *Thermal capacity* of a body is the amount of energy needed to raise the temperature of the whole body by 1 °C.

$$\text{Thermal capacity} = mC$$

It is measured in joule.

10. Principle of calorimetry :

$$\boxed{\text{Heat lost} = \text{Heat gained}}$$

11. The state when no heat flows from one body to another when they are brought in contact with each other is known as the state of thermal equilibrium. In a state of thermal equilibrium, the heat given off by hot substances equals the heat received by cold substances.

12. Equilibrium Temperature $T_c = \frac{C_A m_A T_A + C_B m_B T_B}{C_A m_A + C_B m_B}$

13. All solids expand on heating and contract on cooling but the extent to which they expand or contract is different for different solids. Expansion and contraction of substances, sometimes cause us trouble or even danger, and so we have to devise ways of avoiding these difficulties.

14. When a solid is heated, it generally expands equally in all directions. This change in the dimensions of a body on heating results in the increase in length, area and volume of a body.

    The increase in length is called linear expansion, the increase in area is called superficial expansion and the increase in volume is called cubical expansion.

15. Linear Expansion :

    Change in length $= L_t - L_0 = L_0 \alpha t$

    Coefficient of linear expansion $= \alpha = \frac{L_t - L_0}{L_0 t}$

    Final length $= L_t = L_0 [1 + \alpha t]$

16. Superficial Expansion :

    Change in area $= S_t - S_0 = S_0 \beta t$

    Coefficient of superficial expansion $= \beta = \frac{S_t - S_0}{S_0 t}$

    Final area $= S_t = S_0 [1 + \beta t]$

17. $\beta = 2\alpha$

18. Cubical Expansion :

    Change in Volume $= V_t - V_0 = V_0 \gamma t$

    Coefficient of cubical expansion $= \gamma = \frac{V_t - V_0}{S_0 t}$

    Final Volume $= V_t = V_0 [1 + \gamma t]$

19. $\gamma \approx 3\alpha$

20. Coefficient of linear expansion of a solid is the increase in length per unit length at 0 °C of the solid when its temperature is raised through 1 °C.

    Its unit is per degree centigrade (/°C).

21. The phenomenon of change of state from the solid to the liquid is called fusion or liquefaction whereas the phenomenon of change of state from the liquid to the gaseous or vaporous state is called vaporisation.

22. The quantity of heat required to completely change 1 kg of a solid to liquid at its melting point, without any change in temperature, is known as the latent heat of melting. Latent heat of melting of ice is 334 k J/kg (or 80 cal/g).

23. Latent heat of vaporisation of a substance may be defined as the quantity of heat required to convert 1 kg of the substance from the liquid to the gaseous state, temperature remaining same.

24. The temperature at which a solid changes into a liquid is known as the melting point of the substance, and the temperature at which a liquid changes into a gas is known as the boiling point of that substance.

25. Change of liquid into vapour without the application of heat to it is known as evaporation. It takes place at all temperatures and it always causes cooling.

The rate of evaporation depends on (i) the area of the surface exposed, (ii) the temperature of the liquid, (iii) the wind, (iv) the dryness of the atmosphere, (v) the nature of the liquid.

26. Water vapours are always present in the atmosphere. At any given temperature, air cannot hold more than a definite amount of water vapour. When air holds this maximum amount of water vapour, it is said to be saturated.

27. With increasing temperature, air can hold more water.

28. If at a given temperature a metre cube of air holds m kg of water vapour when it could hold m_s kg on saturation, then

$$\text{R. H.} = \frac{m}{m_s} \times 100\%$$

QUESTIONS

A. Objective Type Questions

1. A temperature of -20°C is the same as the temperature of ____ °F.
2. The unit of heat as a form of energy is ____
3. The average temperature of a human body is ______ °C.
4. The unit of coefficient of linear expansion is _____
5. If 150 cal are added to 1 m^3 of water at 100 °C and standard pressure, the temperature of the water will
   (a) increase
   (b) decrease
   (c) remain the same.
6. The SI unit of specific heat of a substance is ________
7. Q = ______ × m × ______
8. Latent heat of fusion of ice is 334 _______ whereas latent heat of steam is 2260 ______ at the boiling point.
9. The unit of thermal capacity of a body is ________
10. Specific heat of water is 4200 ____________
11. Thermal capacity of a body = mass of the body × __________
12. A body has a mass of 0.1 kg and its specific heat is 420 J/kg °C, its thermal capacity is ___________
13. 1 calorie = _______ J
14. 0.03 cal/g °C = ______ J/kg °C
15. $\alpha = \dfrac{\text{Increase in length}}{\ldots\ldots \times \ldots\ldots}$
16. $\beta = \ldots\ldots \alpha$ and $\gamma = \ldots\ldots \alpha$
17. Joule/k cal is the unit of __________
18. $\text{R. H.} = \dfrac{m}{\ldots\ldots} \times 100\%.$

19. Which of the following statements about water is (are) true ?

(i) Water gives out heat when it is changing to ice at 0°C.
(ii) Water evaporates only at 100°C.
(iii) Water has very low specific heat.

20. The following are five common liquids which could be found in a physics laboratory :

(a) water (b) mercury (c) alcohol (d) ether (e) oil

Which one of the five liquids mentioned

(i) evaporates most easily at room temperature ?
(ii) has a specific heat of 4200J/kg °C ?
(iii) is used in a thermometer suitable for human bodies ?

21. Which of the following units listed for the quantities below is (are) correct ?

(i) Specific heat : $\mathrm{Jkg^{-1}\ {}^{\circ}C^{-}}$
(ii) Latent heat : $\mathrm{J\ kg^{-1}}$
(iii) Coefficient of linear expansion : $\mathrm{{}^{\circ}C^{-1}}$

22. "The ice-point is chosen as one of the fixed points of a thermometer scale because

(A) the mercury level is at its lowest point when the thermometer is placed in ice.

(B) it is an accurate, easily reproducible temperature.

(C) it is the coldest temperature that can exist.

(D) all ice has a temperature of 0 °C.

(E) ice has zero heat energy.

23. When a metal plate, with a square hole at its centre, is heated uniformly the square hole will

(i) become rectangular in shape and increase in size.

(ii) become rectangular in shape and decrease in size.

(iii) remain square and remain the same size.

(iv) remain square and decrease in size.

(v) remain square and increase in size.

24. A bimetallic strip of brass and invar which is straight at room temperature will become curved when

(i) a current is passed through it for some time.

(ii) it is placed in a deep freezer unit for some time.

(iii) it is placed in a hot oven for some time.

25. Taking the specific heat of water to be $4200\ \mathrm{J\ kg^{-1}\,{}^{\circ}C^{-1}}$, the amount of heat required to raise the temperature of 0.15 kg of water from 15°C to 25°C is

(i) 630 J (ii) 6300 J (iii) 9450 J (iv) 12600 J (v) 15750 J.

26. An uncalibrated thermometer placed alongside a mm scale has the ice and steam points opposite the 6 mm and the 206 mm marks respectively. When the mercury level in the thermometer reaches the 100 mm mark on the scale the temperature is

[A] 40 °C [B] 47 °C [C] 48 °C [D] 50 °C [E] 100 °C

27. When an object is heated, the molecules that make up the object

(i) begin to move faster
(ii) lose energy
(iii) become heavier
(iv) become lighter.

(Choose the correct answer)

28. Heat energy of an object is

(i) the average energy of the molecules of the object

(ii) the total energy of the molecules of the object

(iii) the average velocity of the molecules of the object

(iv) the average potential energy of the molecules of the object.

(Choose the correct answer) [Hints : (i)]

29. Iron and brass are two objects. The temperature of iron is greater than that of brass. This means that

(i) the molecules of iron are moving faster on the average than the molecules of brass.

(ii) the total energy of iron is greater than the total energy of the molecules of brass.

(iii) the average potential energy of iron is greater than the average potential energy of brass.

(iv) the heat content of iron will always be greater than that of brass.

(Choose the correct answer) [Hints : (ii)]

30. Two blocks of lead, one twice as heavy as the other, are both at 50 °C. The ratio of the heat content of the heavier block to that of the lighter block is (a) 0.5 (b) 1 (c) 2 (d) 4.

(Choose the correct answer)

31. The quantity of heat required to change the temperature of 1 kg of substance by 1 °C is called its

(a) specific heat

(b) the total energy

(c) the latent heat

(d) heat of fusion

(e) thermal capacity.

32. When a vapour condenses into a liquid

(i) it absorbs heat
(ii) it evolves heat
(iii) its temperature rises
(iv) its temperature drops.

33. A 20 kg storage battery has an average specific heat of 0.2 kcal/kg °C. When fully charged the battery contains 2 kcal of energy. If the entire energy were used to raise the temperature, its temperature would increase by

(i) 20°C
(ii) 200°C
(iii) 0.5°C
(iv) 0.2°C. [Hints : (iii)]

B. Very Short Answer-Type Questions :

1. What is coefficient of linear expansion ?

2. Does the coefficient of linear expansion depend on the unit of length used ?

3. A brass disc fits in a hole in a steel plate at 20°C. In order to make the disc drop out of a plate, should the disc and plate combination be heated or cooled ?

4. (i) What is a kilocalorie ?

(ii) Name the physical quantity which measures the degree of hotness or coldness in a body.
(iii) What is the unit of heat in S.I. system ?
(iv) Which property of matter is used in making a liquid thermometer ?
(v) How many joules of mechanical work produce 1 calorie of heat ?
(vi) What is the lowest possible temperature on the celsius scale ?
(vii) What is the thermal capacity of 1 kg of water ?

5. What is a calorie ?

6. What is a joule ?

7. What is thermal capacity of a body ?
8. Give a word definition for specific heat ?
9. What is the formula which defines specific heat ?
10. What is the principle of calorimetry ?
11. How is the amount of heat required to produce a given temperature change in a substance calculated ?
12. What change of state is called fusion ?
13. What name is given to the temperature at which fusion occurs ?
14. What is latent heat of a substance ?
15. Define latent heat of fusion of water.
16. Define latent heat of vaporization of water.
17. Give the unit of latent heat of a substance.
18. What is temperature ?
19. What is a thermometer ?
20. Define 'heat'.
21. What is meant by thermal equilibrium ? (A.I.S.S. 1986)
22. What is meant by thermal energy ?
23. Define mechanical equivalent of heat.
24. Define specific heat of a substance.(A.I.S.S. 1986)
25. What is equilibrium temperature ?
26. What is evaporation ?
27. Define relative humidity ?
28. How large is the specific heat of water ?
29. What temperature change takes place during a change of state ?
30. Mention three factors that affect evaporation.
31. What is meant by steam point ?
32. What is meant by ice point ?
33. Mention the names of two useful devices based on linear expansion of solids.
34. What formula can be used to convert Celsius temperature to Fahrenheit temperature ?
35. What is the relationship between coefficient of cubical expansion of glass and its coefficient of linear expansion ?
36. How are quantities of heat measured ?

[*Hints*: Quantities of heat are measured by the effects they produce].

37. Define coefficient of cubical expansion.
38. Name one liquid which is a good conductor of heat. [D.B.S.E.1985].
39. State two uses of latent heat of ice. [A.I.S.E.1983 Compt.].
40. What is the unit of specific heat ? [A.I.S.S.1986]
41. (i) What is the freezing point of water on the Fahrenheit scale and on the Celsium scale ?

[A.I.S.S. 1986]

(ii) What is the temperature of steam on the Celsius scale ?

42. A metal plate has a circular hole. Will the diameter or the hole increase or decrease on heating this plate? [A.I.S.S.1986]

C. Short Answer Type and Essay Type Questions

1. Why is mercury the best liquid for a thermometer ? Why is water considered unsuitable ?

2. Name two scales of temperature and state the upper and lower fixed points of each.

3. Draw and label fully a clinical thermometer.

   Why is a clinical thermometer not sterilised in boiling water like the other instruments used in the hospital?

   What makes it still possible for this thermometer to register the temperature of the body after it has been taken out of the mouth or armpit ?

4. The following readings were obtained in an experiment :

°C	°F
0	32
20	68
40	104
60	140
80	176
100	212

   Draw a conversion graph for the Centigrade and Fahrenheit thermometers. From your graph read the following :

   (a) in °F ; 30°C ; 55°C ; — 10°C ; — 20°C ; 0°C.

   (b) in °C ; 77°F ; 203 °F ; 30°C ; 14°F ; 0°F.

5. Give one experiment to show that solids expand on heating and one to show that all solids do not expand to the same extent on heating. Illustrate with diagrams.

6. A compound bar is made of iron and brass. When the bar is heated, what side will be bent ? Mention one practical application based on this principle.

   How would you show that a liquid expands on heating ?

7. Answer the following questions :

   (a) Why are gaps left between railway lines ?

   (b) Why are concrete roads marked off into blocks and the cracks filled with tar ?

   (c) When a glass stopper sticks to the bottle so that it is difficult to remove, what would you do to remove it easily and why ?

   (d) Why is it impossible to seal a brass wire into a glass rod while it is possible to seal a platinum wire into it ?

   (e) Would a single large sheet of copper or aluminium be satisfactory to cover one-half of the roof on a house ?

   (f) Which is more likely to break when put in boiling water and why : a thick glass vessel or a thin one ?

   (g) When electric wires are being strung on poles on a hot day, should they be drawn very tight or be allowed to sag ? Why ?

8. How would thermometer readings be affected if equal volumes of mercury and glass expanded equally when raised through the same temperature ?

9. Is it true to say that all liquids expand to the same extent when heated ? Illustrate your answer with an experiment.

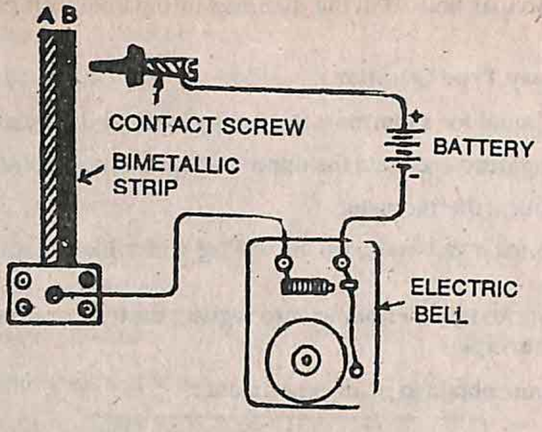


Fig. 8.22

10. The time recorded by a pendulum depends upon the length of the pendulum. Should changes in the weather affect the time ? In what way will it be affected ?

11. The time recorded by a watch depends on the radius of the balance wheel. Would changes in the weather affect the time ? In what way will it be affected ?

12. Figure 8.22 consists of a bimetallic strip AB with a contact screw almost touching it. Both are connected to an electric bell and a battery. Explain how the arrangement can be used as an automatic switch (*i.e.*, a switch operating at a particular temperature). Suggest materials for A and B, the components of the bimetallic strip.

13. A motorist stopped at a petrol filling station and had cold water added to the radiator of his car. He drove above 120 km and stopped. He noticed that water was dripping from the overflow pipe of the radiator. Explain.

14. Mention some of the practical applications of
    (i) expansion of solids
    (ii) expansion of liquids.

15. Define :
    (i) Linear expansion of a solid
    (ii) Temperature
    (iii) Heat or Thermal Energy

16. Explain :

    Why cheap clocks run slow in summer and fast in winter.

17. Define : Coefficient of superficial expansion and coefficient of cubical expansion and prove that $\beta = 2\alpha$ and $\gamma = 3\alpha$

18. Mention the units of

    (i) Heat (ii) Coefficient of linear expansion (iii) Coefficient of superficial expansion (iv) Coefficient of cubical expansion (v) Thermal capacity.

19. (a) Distinguish between heat and temperature.
    (b) Name the instrument that measures temperature.
    (c) Is the coefficient of linear expansion different for different solids ?

20. (a) What are the factors upon which the quantity of heat communicated to a substance (which does not melt or vaporise) depends ?
    (b) What is heat ? Give the units of specific heat in the c.g.s. system and SI system of units.

(c) Define : (i) calorie (ii) kilo-calorie (iii) joule (iv) Specific heat of a substance (v) Thermal capacity of a body.

21. (a) What is the Principle of Mixtures or Principle of Calorimetry ?

(b) Define : Latent heat of a substance ; Latent heat of fusion of ice and Latent heat of vaporisation of steam.

22. Distinguish between

(i) Fusion and Vaporisation
(ii) Melting and Boiling
(iii) Evaporation and Boiling
(iv) Melting point and Boiling point

23. (a) What are the factors upon which evaporation depends ?

(b) 'Evaporation causes cooling'. Explain this statement and give one experiment to demonstrate that evaporation causes cooling.

24. Give reasons for the following :

(i) Why does ice appear colder than ice-cold water and steam appear hotter than boiling water ?
(ii) Why is latent heat of steam so high as compared to ice ?
(iii) Why does an earthen pot keep water cool in summer ?

OR

Water in an earthen vessel attains a lower temperature than the room temperature.
[A.I.S.S. 1986]

(iv) Why is water used in hot water bottles for fomentation ?
(v) Why do dogs hang out their tongue in summer ?
(vi) Why is calorimeter placed in a wooden box ?
(vii) Why does temperature fall below 0°C when common salt is added to ice ?
(viii) Can water be made to boil without heating it ?

25. Write down the values of the following :

(a) L.H. of water = ...
(b) L.H. of steam = ...
(c) Melting point of ice = ...
(d) Boiling point of water = ...

26. (a) How many joules of mechanical work produce 1 calorie of heat ? (A.I.S.E. 1982)

(b) Is the specific heat of ice greater than that of water ?

(c) What is the meaning of the statement that the specific heat of lead is 0.03 cal per gm per °C ?

27. Why does the latent heat of vaporization vary with the boiling temperature ?

28. Why does steam at 100° C produce a more severe burn than water at 100 °C ?

29. Why does an easily vaporized liquid such as ether feel cool to the skin ?

30. Why is ice at 0°C more effective in cooling than water at 0°C ?

31. (a) Can we develop a device based on our sense of touch to measure temperature of a body ?

(b) Who developed the first thermometer ? What was its principle ? Explain.

32. (a) How would you demonstrate the presence of water vapour in the atmosphere ?

(b) When does air become saturated ? Define the term relative humidity.

(c) How do we feel when the relative humidity is high ? At what percentage humidity do we feel comfortable ?

33. Set up an activity to study the heating of ice and water and hence define latent heat of melting and latent heat of vaporization with the help of a graph.

34. Explain the following :

(i) Why are sparks seen when a piece of metal is held against a turning grindstone ?
(ii) The nose of a supersonic aircraft is made of titanium steel to stand up to the high temperatures expected when flying at twice the speed of sound. Why is there an increase of temperature ?
(iii) The thermostat controls the temperature of the electric iron; can you explain how it works ?
(iv) A housewife wants the potatoes to cook more quickly. The water is already boiling. Is it sensible for her to turn up the gas so that the saucepan receives more heat ? Why ?
(v) Wet your finger, hold it up in the air. How would you decide which way the wind is blowing ?
(vi) A sheet of glass is heated strongly at its centre. What happens to the glass ?
(vii) In what way is liquid affected by heat, and how is this phenomenon used in thermometers ?

35. What is heat energy ?

[Hints : (1) Heat is a form of energy. Other forms of energy such as chemical, sound, light and electrical energy usually finish up as heat.

(2) Heat causes most substances to expand, whether solid, liquid or gas.
(3) Heat can make solids melt and become liquids, and it can make liquids boil and becomes gases.
(4) Heat can make a liquid change into a gas at all temperatures — evaporation.]

36. When a clinical thermometer is taken out of the mouth of a patient mercury level does not fall on its own. Why ? (A.I.S.E. 1985)

37. What is a bimetallic strip ? How does it provide an automatic make and break in an electrical circuit ? (A.I.S.E. 1985,1986)

38. State two uses of high specific heat of water. (A.I.S.E. 1983)

39. (a) What do you understand by the term linear expansion and cubical expansion of a solid ?

(b) What is the S.I. unit of heat energy ? [A.I.S.E. 1981 (c)]

40. What is the S.I. unit of temperature ? (A.I.S.E. 1981)

41. Describe the Celsius scale of temperature. (A.I.S.S. 1986)

PROBLEMS

1. Convert 95° F, 81° F, 122° F into Centigrade (or Celsius) scale. [Ans. 35 °C;27. 2 °C; 50 oC]

2. Convert 25 °C; 35° C; 45° C; – 273° C into Fahrenheit scale. [Ans. 77 °F; 95 °F; 113 °F; – 460 °F]

3. At what temperature will the reading on the Fahrenheit thermometer be double that of a Celsius one ? [Ans. 320 °F]

4. An accurate Celsius thermometer registers 15·5° C, while a faulty Fahrenheit thermometer, hanging beside it, registers 61·5° . What is the correction to be applied to the later reading ? [Ans. –1·6°F]

5. When the temperature is 0° C, a thermometer reads 0.5° C, while at 100° C it reads 100.8° C. Find the true temperature when the thermometer reads 20° C, assuming that the bore is cylindrical and divisions are of uniform length. [Ans. 19.44 °C]

[Hints : Error at 20°C $= 0.5 + (.8 - .5) \times \frac{20}{10}$]

6. The length of a copper rod at 50° C is 2.00166 m and at 200° C it is 2.00664m. Find its length at 0° C and the coefficient of linear expansion of copper. [Ans. 2 m; 0.0000166 per °C]

7 The height of barometer having a brass scale is found to be 77.25 cm at 25° C. Find the true height at °C ? α for brass = 0.0000187 per °C. [Ans. 76.94 cm]

8. What space must be left between two railway lines 20 m long, laid at 15° C to allow for expansion upto 50 °C. Coefficient of linear expansion of the material is $1.5 \times 10^{-3}/ °C$? [Ans.1.05 m]

9. A steel scale gives correct measurement at 50° F. What will be the length of a rod, which measures 1 metre at 10 °C, with this scale ? Coefficient of linear expansion of steel = 0.000012 °C. [Ans. 0.9994 m]

10. A copper disc at 0° C has a diameter of 1 m and a hole cut in the centre is 0.1 m in diameter. What will be the diameter of the hole at 100 °C ? α for copper = 0.000016 per °C. [Ans. 0.10016 m]

11. Calculate the change in length of an iron rail of length 13 m when its temperature changes from 5°C to 45° C. α for iron = $12 \times 10^{-6}/°C$. [Ans. 6.24 mm]

12. What is the final temperature of water if we pour 2 litres of water at 80° C in a plastic bucket containing 10 litres of water at 20° C. Ignore the heat taken by the bucket. [Ans. 30 °C]

[Hints : mass = volume x density]

13. A cube of copper weighing 0.1 kg. is placed for sufficient time in a vessel containing boiling water. The temperature of the cube then is 100° C. It is taken out and immediately transferred to another metallic vessel containing 0.25 kg of water at 20° C. The temperature of water rises and attains a steady value of 23° C. What is the specific heat of copper ? Given : the specific heat of water = $4{\cdot}2 \times 10^{3}$ J/kg °C. Ignore the heat taken by the metal vessel into which the copper block is dropped. [Ans. 0.409×10^{3} J /kg° C]

14. A mass of 0.7 kg. of copper at 98°C is put into 0.8 kg of water at 15° C contained in a copper vessel weighing 200 g and the final temperature is noticed to be 21° C. Find the specific heat of copper. Specific heat of water = 4200 J/kg °C [Ans. 382 J/kg °C]

15. If an object consists of 5·5 kg. of iron and 3.3 kg of aluminium and contains 2.0 kg. of water, how much heat (energy) will raise the whole thing by 20°C ? Specific heats for iron, aluminium and water are 500 J/kg °C, 880 J/kg °C and 4180 J/kg °C respectively. [Ans. 28×10^{4} J]

16. (a) When 4000 J are put into 0.125 kg of water, by how much would the temperature rise ? Specific heat of water = 4180 J/Kg° C.

(b) If the same energy was put into the same mass of steel, what would the temperature rise be ? Specific heat of steel = 447 /Kg°C. [Ans. (a) 32°C (b) 72 °C]

17. (a) Find the thermal capacity of an object if, after it is heated to 100°C, it is put into 0.400 kg of water at 10° C and the water temperature goes to 25°C. Specific heat of water = 4180 J/kg°C.

(b) If the object has a mass of 0.37 kg, what is its specific heat ?

[Ans. (a) 334.4J/°C (b) 903.8 J/kg°C]

18. Find the temperature that results when 12 kg of water at 90° C are put into 30 kg, of water at 25° C. Neglect the heat absorbed by the container. [Ans. 43.6° C]

19. (a) How many joules are required to change 0.50 kg of ice at 0°C to water at 0°C ?

(b) When 0.50 kg of ice is put into 1·5 kg of water at 20°C, what will the result be ?

L.H. of ice = 334 kJ/kg

Specific heat of water = 4200 J/kg °C.

[Ans. (a) 167 kJ (b) only 0.37 kg of ice will melt and the mixture will remain at 0 °C]

20. If 3.0 grams of steam are added to 0.150 kg of water in a calorimeter, resulting in condensation, what temperature rise will result ? The water is initially at 15°C. Ignore the heat gained by the calorimeter.

Latent heat of steam = 2260 kJ/kg

Specific heat of water = 4200 J/kg °C [Ans. 27.2°C]

21. Find the energy required to change 1 kilogram of water from the ice form at – 10°C to steam at 100°C.

The specific heat of ice = 2090 J/kg° C

Latent heat of vaporization of water = 2260 kJ/kg

Latent heat of fusion of water = 334 kJ/kg

Specific heat of water = 4200 J/kg° C [Ans. 3.0349 x 10^6J]

22. What is the thermal capacity of 0.15 kg of aluminium if its specific heat is 919.8 J/kg °C.[Ans. 137.9 J/ °C]

23. How much heat must be added to 1 kg of copper to raise its temperature from 20°C to 100°C ? Specific heat of copper = 390.8 J/kg °C [Ans. 31248 J]

24. Air at 30°C has a relative humidity of 70%. One m^3 of saturated air at 30°C contains 15 g of water. How much water will 1 m^3 of air hold at 30°C ? [Ans. 10·5 g]

25. What is the amount of heat energy required to boil 1 kg of ice which is at 0°C ? Latent heat of ice is 80 kcal/kg and latent heat of steam is 540 kcal/kg. [Ans. 720 k cal] [A.I.S.E. 1985]

26. The length of an iron rod is 50 m at 0°C. If the coefficient of linear expansion of iron is 12×10^{-6} °C^{-1}, what will be its length at 10 °C ? [Ans. 50.0006 m] [A.I.S.E. 1985]

27. The coefficient of linear expansion of copper is 17×10^{-6} / °C. What will be its coefficient of cubical expansion ? [Ans. 51×10^{-6} /° C][A.I.S.E. 1985]

28. Silver and copper pieces (specific heat 0.056 and 0.093 k cal per °C respectively) of equal mass, initially at the same temperature, are supplied the same amount of heat. Which one will attain a higher temperature? [Ans. Silver] [A.I.S.E. 1985]

29. If the coefficient of cubical expansion of a material is 5.4×10^{-5} per kelvin, what is its coefficient of linear expansion ? [Ans. 1.8×10^{-5} /K] [D.B.S.E. 1985]

30. How much heat is required to raise the temperature of a copper vessel of mass 0.05 kg through 40°C ? The specific heat of copper is 0.09 k cal kg^{-1} °C^{-1}. [Ans. 0.18 k cal] [A.I.S.E. 1985]

31. A scale made of steel is exactly 100 cm long at 30°C. What would be its length at 0°C ? Coefficient of linear expansion of steel is 1.2×10^{-5} / °C. [Ans. 99.96 cm] [A.I.S.E. 1986]

CHAPTER 9

ELECTRICITY AND ITS EFFECTS

LEARNING OBJECTIVES

At the completion of this Chapter, you should be able to grasp :

(i) that electricity is one of the most convenient and important source of energy.

(ii) the distinction between conductors and insulators ; conductors and resistors.

(iii) the concept of electric potential and the definition of volt.

(iv) the relationship between electric current, electric potential and resistance (Ohm's law) and its applications.

(v) the usage of devices like ammeter and voltmeter in an electrical circuit.

(vi) the idea that an electric circuit transfers energy (heating effect of electric current) and that the heating effect of electric current is made use of in all electrical heating devices.

(vii) the concept of electrical power and its units – *watt* and *kilowatt*. The electric energy consumed is measured in *kilowatt hour* (kWh).

(viii) the concept that electricity produces magnetism (electro-magnetism).

(ix) Maxwells' right-hand rule and Fleming's left-hand rule and their applications – electric motor.

(x) the concept of electromagnetic induction (magnetism produces electricity).

(xi) the principle (Right-hand rule) and the working of an electric generator (dynamo) and electric power plants.

(xii) the elementary ideas about domestic electric circuit – wiring, fuses and safety measures.

(xiii) the idea that electricity could be dangerous if certain precautions and safety measures are not observed while using it.

9.1 INTRODUCTION

Tremendous progress has been made since the days when the study of electricity was concerned mainly with static electricity and with current electricity turning motors and heating wires. The practical applications of electricity are numerous and well-known. The object of this Chapter is to introduce students to the study of static and current electricity in such a way that various phenomena observed in daily life and concerned with this aspect of nature can be understood.

The concepts of charge, field intensity and potential have been introduced in static electricity. The current as a flow of charges, resistance and potential difference are the three basic concepts which have been dealt with in current electricity. The sources of current – its various effects, simple circuits and their practical applications have also been discussed.

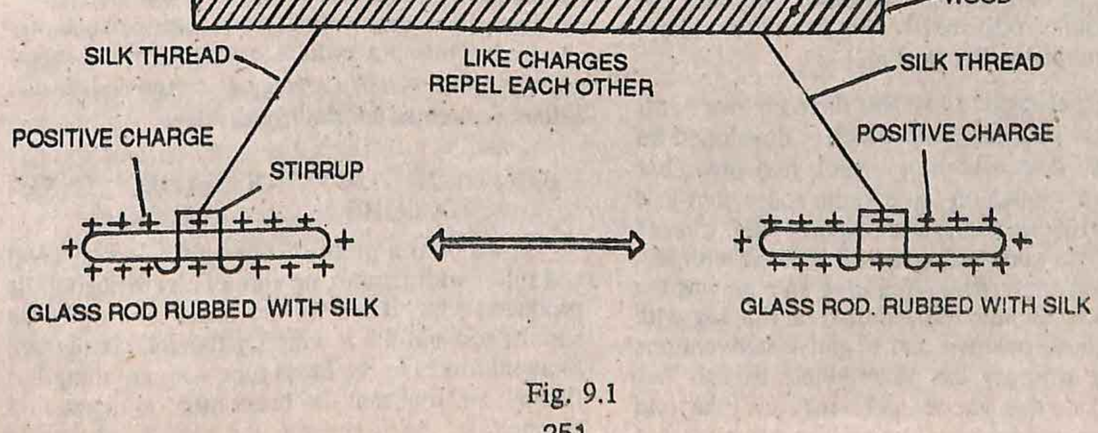
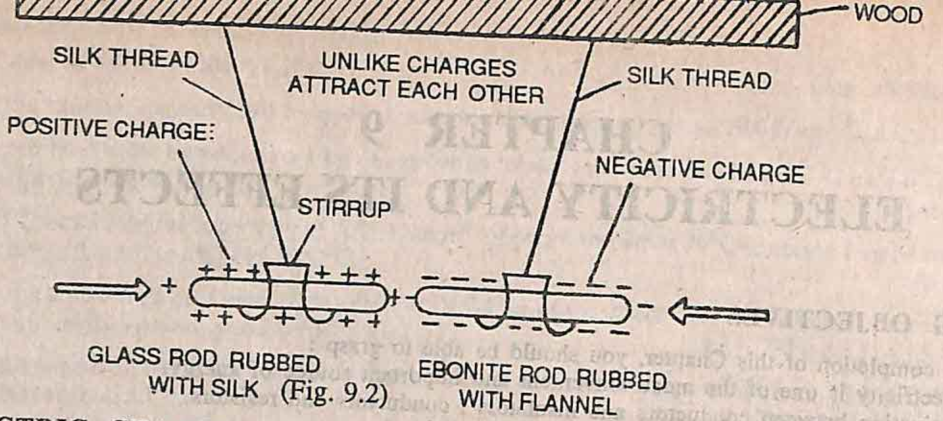

WOOD
SILK THREAD
LIKE CHARGES REPEL EACH OTHER
SILK THREAD
POSITIVE CHARGE
STIRRUP
POSITIVE CHARGE
GLASS ROD RUBBED WITH SILK
GLASS ROD. RUBBED WITH SILK

Fig. 9.1


WOOD
SILK THREAD
UNLIKE CHARGES ATTRACT EACH OTHER
SILK THREAD
POSITIVE CHARGE
NEGATIVE CHARGE
STIRRUP
GLASS ROD RUBBED WITH SILK
EBONITE ROD RUBBED WITH FLANNEL

(Fig. 9.2)

9.2 ELECTRIC CHARGE

It was discovered by Thales, about 600 B.C., that when amber was rubbed with flannel or catskin, it acquired the property of attracting light objects, such as pieces of paper, cork, etc., and it is from *electron*, the Greek word for amber, that the term electricity is derived. But, now we know that this property is shared by many other substances, such as glass, ebonite, sealing wax, etc., when they are rubbed under suitable conditions. A substance which exhibits this property is said to be *electrified* or *charged* and the mysterious agent, which causes this state of the body, is known as *static electricity*. A body, which does not possess this property, is said to be *neutral*.

Rub a glass rod with silk and place it in a stirrup, suspended by a silk thread. Now, rub another glass rod with silk and bring it near the charged end of the first by placing it in another stirrup suspended by another silk thread as shown in (Fig.9.1). It will be seen that the suspended rods are *repelled* from each other. This force acts even when the two rods are some distance apart. It would still act if they were in *a vacuum*. If an ebonite rod is rubbed with flannel, its subsequent behaviour is different. Two ebonite rods so treated repel each other, just as two glass rods rubbed with silk do, but an ebonite rod rubbed with flannel attracts a glass rod rubbed with silk (Fig.9.2)

The experiments show that there are *two kinds of electrical charges* ; one which is developed on glass when it is rubbed with silk and the other which is developed on the ebonite rod, when it is rubbed with flannel. Historically the charge acquired by a glass rod after it is rubbed with silk was defined as *positive. Negative charge* was the one which an ebonite rod acquired on rubbing with flannel. These positive and negative conventions are purely arbitrary but nevertheless useful. We, thus, conclude that *like charges repel each other and unlike charges attract each other*. These forces act at a distance.

The fact is that every material, whether charged or not, already contains vast amount of electric charge. If it is electrically neutral, this is merely because the charge is there in exactly *equal* amounts of positive and negative. It is electrical force which holds the atoms together in a solid and every atom itself consists of positively charged nucleus with negatively charged electrons moving around it, held to the nucleus by electrical attraction. Charging processes (by rubbing) consist of transfer of *free electrons*. When a glass rod rubbed with silk acquires a positive charge, this is because it surrenders some electrons to the silk, which consequently acquires equal negative charge. If you test the piece of silk with which the glass rod was rubbed by bringing it close to an ebonite rod rubbed with flannel, you will find the charge on the silk to be negagive. Similarly the piece of flannel with which the ebonite rod is rubbed acquires positive charge. Detailed studies have shown that in each case the positive and negative charges produced by rubbing the two materials are *equal* in magnitude. It is thus clear that the process of rubbing does not create electric charge. It results in only transferring negative charges from one material to the other. The material from which the negative charges have been transferred is left with an excess of positive charge. The material which receives the negative charges becomes negatively charged. This is a typical example of a general principle that *electric charge is conserved. It can neither be created nor destroyed.*

9.3 CONDUCTORS AND INSULATORS

If we hold a piece of brass tube in one hand and rub it with flannel, no sign of electrification is produced ; but if we fix the brass tube on to an ebonite rod and rub it with dry flannel, taking care to avoid touching the brass tube with anything but flannel, we find that the brass tube is negatively charged. In the first case, the electric charge is certainly produced by friction but since the brass tube, the human body, and the earth are all connected, the electric charge spreads itself over the brass and passes through the human body on to the earth and so the brass shows no signs of electrification. In the second case also, the electric charge is produced by friction but is prevented from passing to the earth by the ebonite handle and the tube thus remains charged. This shows that, with respect to the passage of an electric charge through them, substances can be divided into two classes : *conductors and insulators.*

A **conductor** *is a material through which an electric charge is readily transferred.* Most metals are good conductors. At normal temperatures, silver is the best solid conductor ; copper and aluminium follow in that order. Gold, human body and graphite are also important conductors. Solutions of inorganic salts in water are good conductors as well. Earth is regarded as one huge conductor. A body which is connected to the earth by means of conducting communication is said to be *earthed or earth connected.*

An **insulator** *is a material through which an electric charge is not readily transferred.* Good insulators are such poor conductors that for practical purposes they are considered to be non-conductors. Glass, mica, paraffin, hard rubber, sulphur, silk ; shellac ; dry air, ebonite ; oils, quartz and many plastics are good insulators. Pure water is a non-conductor but ordinary water, on account of dissolved impurities, is a good conductor.

It should be noted that the difference between conductors and insulators, although sometimes very marked, is one of degree. No substance is so good a conductor as not to offer any resistance to the passage of an electric charge through it. On the other hand, no substance is a perfect insulator. For instance a glass rod will also allow the electric charge to flow along it if a *high electrical pressure* is applied at its ends. There are certain substances whose property of carrying charges lies between conductors and insulators. Such substances are cotton, dry wood, paper etc. The student should realize that the precise formulation of the motion of charges in solids is a very complex problem. In fact the exact behaviour of charges (electrons) in solids is still an active field for research to-day, particularly for the substances which are intermediate between conductors and insulators, the so-called *semi-conductors.*

9.4. COULOMB'S LAW OF FORCE BETWEEN CHARGES

We have seen that two similar charges repel each other and two dissimilar charges attract each other. The force of attraction or repulsion obeys the following law known as *coulomb's law of force between charges* due to Charles Coulomb (1736-1806). Coulomb's law states that the **force between two electric charges is proportional to the product of the charges and inversely proportional to the square of the distance in vacuum between them.**

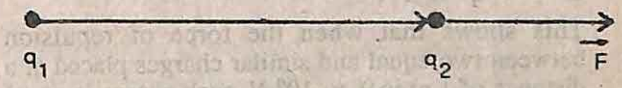


Fig. 9.3.

If a charge q_1 is at a distance r from a second charge q_2 then the force on q_2 (Fig 9.3) is

$$\boxed{\vec{F} = K\frac{q_1q_2}{r^2}} \qquad ...(1)$$

where K is the constant of proportionality. In S.I. units, the charge is measured in coulombs and K has the experimentally determined value

$$K = 9.0 \times 10^9 \, Nm^2C^{-2}$$

The force is *attractive* if q_1 and q_2 have *opposite* signs and it is *repulsive* if they have *like* signs. It is directed along the line joining the centres of the two charged bodies.

If we are interested only in the *magnitude* of the force of attraction or repulsion between two electric charges, then it will be given by

$$\boxed{F = K\frac{q_1q_2}{r^2}} \qquad ...(2)$$

where $K = 9 \times 10^9 \, Nm^2/C^2$ in S.I. units

Note that

$$\overrightarrow{F_{12}} = -\overrightarrow{F_{21}},$$

which shows that the force on q_1 due to q_2 is equal but opposite to that on q_2 due to q_1.

When a charge q_2 (Fig. 9.3) is near two or more additional charges, the net force on q_2 is the *vector sum* of the forces due to each of the other charges.

Unit Charge

Suppose we take two similar charges each equal to q and place them in vacuum (or air) at a distance of 1 m. If the force of repulsion between them is 9 × 10^9 N, then for equation (2).

$$q_1 = q_2 = q$$
$$r = 1\text{ m}$$
and $$F = 9 \times 10^9\ N$$

Thus from equation (2), we have

$$9 \times 10^9 = 9 \times 10^9 \frac{q^2}{(1)^2}$$
or $$q^2 = 1$$
or $$q = \pm 1$$

This shows that when the force of repulsion between two equal and similar charges placed at a distance of 1 m is 9 × 10^9 N, each charge is equal to unity. Hence,

"A unit charge is that charge which when placed in vacuum (or air) at a distance of one metre from a similar and and an equal charge repels it with a force of 9 × 10^9 newtons" This is known as the **coulomb** (C) . It is the unit of electric charge in S.I. units. Note that 1 coulomb is an enormous charge. The elementary unit of charge used in atomic physics is charge on an electron *i.e* ., $1{\cdot}602 \times 10^{-19}$ coulomb. It is interesting to note that 1 coulomb of charge contains

$$\frac{1}{1{\cdot}6 \times 10^{-19}} = 6{\cdot}25 \times 10^{18} \text{ electrons.}$$

Frequently, it is convenient to work with a fraction of coulomb called the *micro-coulomb* (μC)

$$(\mu C) = 10^{-6} C$$

9.5 ELECTRIC FIELD

Electric forces, like the gravitational forces, act between bodies that are not in contact with each other. The proper way to regard such forces involves the concept of a **force field.** When a mass is present somewhere, the properties of space in its vicinity can be considered to be so altered that another mass brought to this region will experience a force there. The 'alteration in space' caused by a mass is called its gravitational field, and any other mass is thought of as interacting with a field and not directly with the mass responsible for it. Similarly an electric charge produces an **electric field** around it that interacts with any other charges present. *Thus electric field is the space surrounding a charged body within which its influence is felt.*

One reason it is preferable not to think of two charges as exerting forces upon each other directly is that if one of them is changed in magnitude or position, the consequent change in the forces each experiences does not occur immediately, but takes a definite time to be established. This delay cannot be understood on the basis of the Coulomb's Law but is easily accounted for in terms of the field concept by assuming that the changes in the field travel with a finite speed *i.e.*, the speed of light, 3 × 10^8 m/s.

If we place a point charge in an electric field some force acts on it. The magnitude of this force depends upon the strength of the electric field and the strength of the charge. To measure the strength of the electric field or the **electric intensity** at a point, we place *a unit positive charge* (or *a test charge*) at that point. The force experienced by this charge measures the electric intensity at that point. Electric intensity is a *force* ; hence it is a **vector** quantity and thus has got a *direction*. The direction in which the unit positive charge moves when free to do so gives the direction of intensity. Hence,

"The intensity of the electric field at a point in an electric field is the force experienced by a unit positive charge placed at that point. The direction of the electric intensity is the direction in which the unit positive charge begins to move if free to do so.

We can use Coulomb's Law to determine the *magnitude of the electric field* surrounding a single charge q. We find the force F that q exerts upon a unit positive charge (*test charge*) at a distance r away is

$$\vec{F} = K\frac{q \times 1}{r^2}$$

which is directed from the charge q towards the point where the test charge is located.

or $$\boxed{\vec{F} = \frac{Kq}{r^2}}$$

where $K = 9 \times 10^9\ Nm^2C^{-2}$

This by definition is the electric field intensity $\vec{E}$ at a distance r from the charge q.

$$\boxed{\therefore \text{ Electricity field intensity} = \vec{E} = \frac{Kq}{r^2}}$$

The *magnitude* of electric field intensity is given by

$$\boxed{E = \frac{Kq}{r^2}}$$

If *q is positive*, $\vec{E}$ *points* away from q ; if q is *negative* $\vec{E}$ points toward q. *The electric field due to a charge points away from the charge if it is positive, and toward it if the charge is negative.*

It is expressed in *newton per coulomb i.e.*, NC^{-1} in S.I units. Electric field intensity falls off inversely as r^2.

Once we know the electric field intensity $\vec{E}$ at any point in an electric field, we can easily find the force $\vec{F}$ acting on any charge q placed at a point *i.e.*,

$$\boxed{\vec{F} = q\vec{E}}$$

When there are several charges $q_1, q_2, \ldots$ at various positions, the electric field $\vec{E}$ at a point is the *vector sum* of the individual electric fields $\vec{E}_1, \vec{E}_2, \ldots$ due to all the charges.

9.6 ELECTRIC LINES OF FORCE

Let us consider a positively charged sphere isolated in space, $+Q$ of [Fig 9.4 (*a*)]. All small positive charge $+q$, which we shall call a *test charge*, is brought near the surface of the sphere. Since the test charge is in the electric field of the sphere and the charges are similar, it experiences a repulsive force *directed radially* away from $+Q$. Where the charges on the sphere negative, as in [Fig. 9.4(*b*)], the force acting on the test charge would be directed radially toward $-Q$.

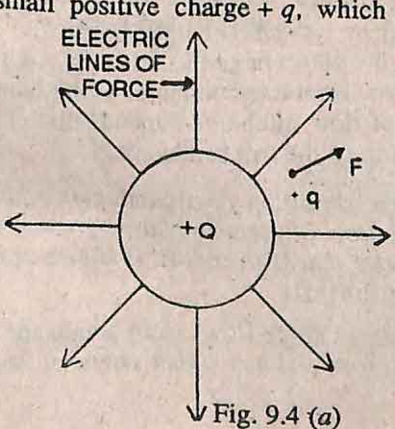


Fig. 9.4 (*a*)

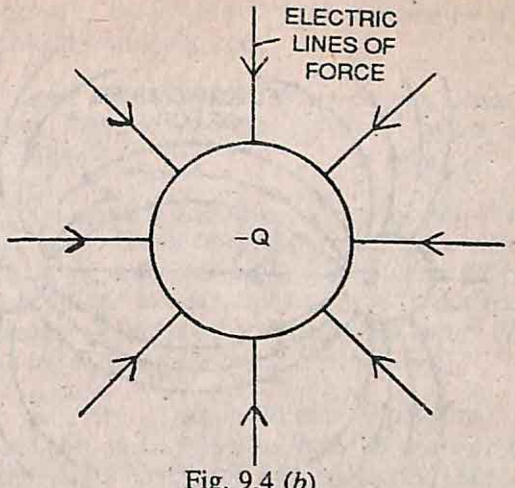
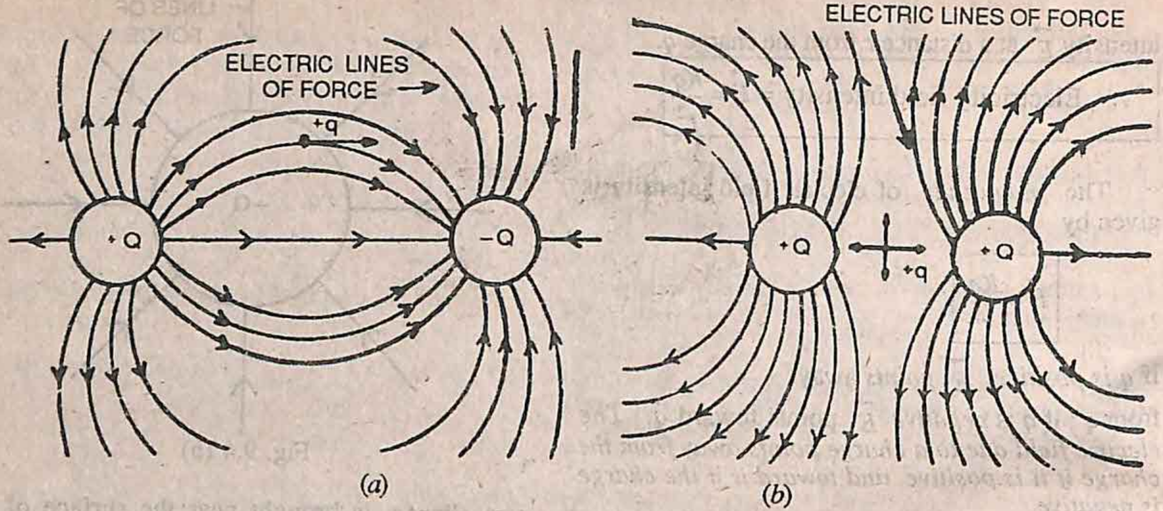


Fig. 9.4 (*b*)

An **electric line of force** *is a line so drawn that a tangent to it at any point indicates the orientation or direction of the electric field at that point.* We can imagine a line of force as the path of a test charge moving slowly in a very viscous medium in response to the force of the field. By convention, electric lines of force *originate* at the surface of a positively charged body and *terminate* at the surface of a negatively charged body, each line of force showing the direction that a positive test charge would be accelerated in that part of the field. A line of force must therefore be *normal* to the surface of the charged body where it joins that surface.

The *intensity*, or strength of an electric field, as well as its direction, can be represented graphically by lines of force. *The electric field intensity is proportional to the number of lines of force per unit area normal to the field.* Where the intensity is high, the lines of force will be close together. Where the intensity is low, the lines of force will be more widely separated in the graphical representation of the field.

In Fig. 9.5 (*a*) electric lines of force are used to show the electric field near two equally but oppositely charged objects. At any point in this field the resultant force acting on a test charge $+q$



(*a*) (*b*)

Fig. 9.5

can be represented by a vector drawn tangent to the line of force at that point.

The electric field near two objects of equal charge of the same sign is shown by the lines of force in [Fig 9.5 (*b*)]. The resultant force acting on a test charge $+q$ placed at the mid-point between these two similar charges would be zero.

The following properties are attributed to the electric lines of force :

(*i*) They start from the positive charge and end at the negative charge.

(*ii*) Two electric lines of force never intersect each other.

(*iii*) There are no electric lines of force inside a hollow conductor.

(*iv*) Number of electric lines of force per unit area gives a measure of the electric field intensity (extent of the influence of the charge) at a point in that area.

(*v*) They have the properties of longitudinal contraction and lateral repulsion.

These electric lines of force are all *imaginary* but they indicate the direction in which the electric field in the space is acting. They are very useful in explaining various electrical phenomena, *e.g.*, attraction between two unlike charges is explained by the property of longitudinal contraction ; repulsion between two like charges is explained by the property of lateral repulsion and electrical induction is explained by the fact that lines of force leaving a positive charge when fall on one end of a good conductor produce a negative charge there and these lines then flow through the conductor and leave it at the other end and charge it positively. If, however the conductor is earthed, *the inductive action does not travel forward.*

9.7 ELECTRICAL POTENTIAL DIFFERENCE

When we raise a body from the ground to a certain height, we do a certain amount of work on the body. This increases its potential energy. Therefore, a point at a higher level means a point of greater potential energy or a higher gravitational potential. Now we know that a body if left to itself falls down from a point of greater potential energy or higher gravitational potential to a point of lower gravitational potential. Similar is the case with electricity. Suppose we have two insulated conductors *A* and *B* charged positively. If we place them in contact or connect then by a wire, *charge* will flow from one conductor to the other. The direction of flow of charge depends upon the *electric condition of* the two conductors.

The electric condition of a conductor which determines the flow of electric charge from it to another conductor placed in contact is known as its **electrical potential.**

If the positive charge flows from conductor *A* to conductor *B*, then *A* is at a *higher* potential than

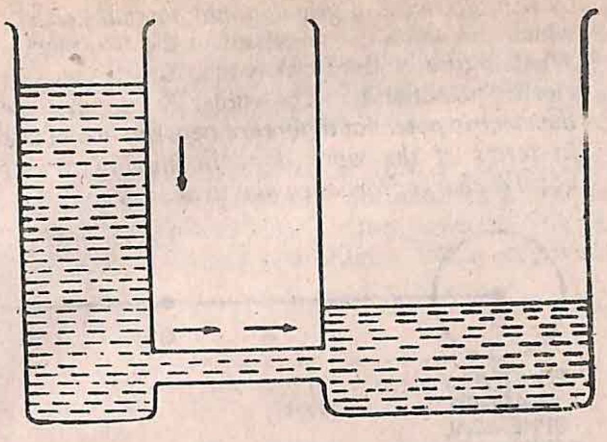


Fig. 9.6

B. The flow of charge continues as long as the potential of *A* remains higher than of *B* and stops as soon as the potential of the two conductors becomes the same.

Electric potential is *analogous* to level in the case of water, to temperature in the case of heat and to pressure in the case of gases.

Activity. Take two cylindrical vessels containing water (Fig 9.6) connected by a tube provided with a stop-cock.

Open the stop-cock. What do you observe ? What happens to the flow of water after sometime ?

On opening the stop-cock, you will observe that water flows from the vessel in which the surface of water has *higher level* than the other even though the quantity of water in the former vessel may be less than that in the latter. *There will be no flow if the levels are the same.*

Activity. Take small copper piece and heat it red hot. Place it in a bucketful of water at room temperature containing a thermometer. What do you observe ? What happens to the flow of heat after sometime ?

You will observe that heat will flow from the copper piece to the water, though the quantity of heat in the water may be much greater than that in the copper piece. Heat flows from the copper piece

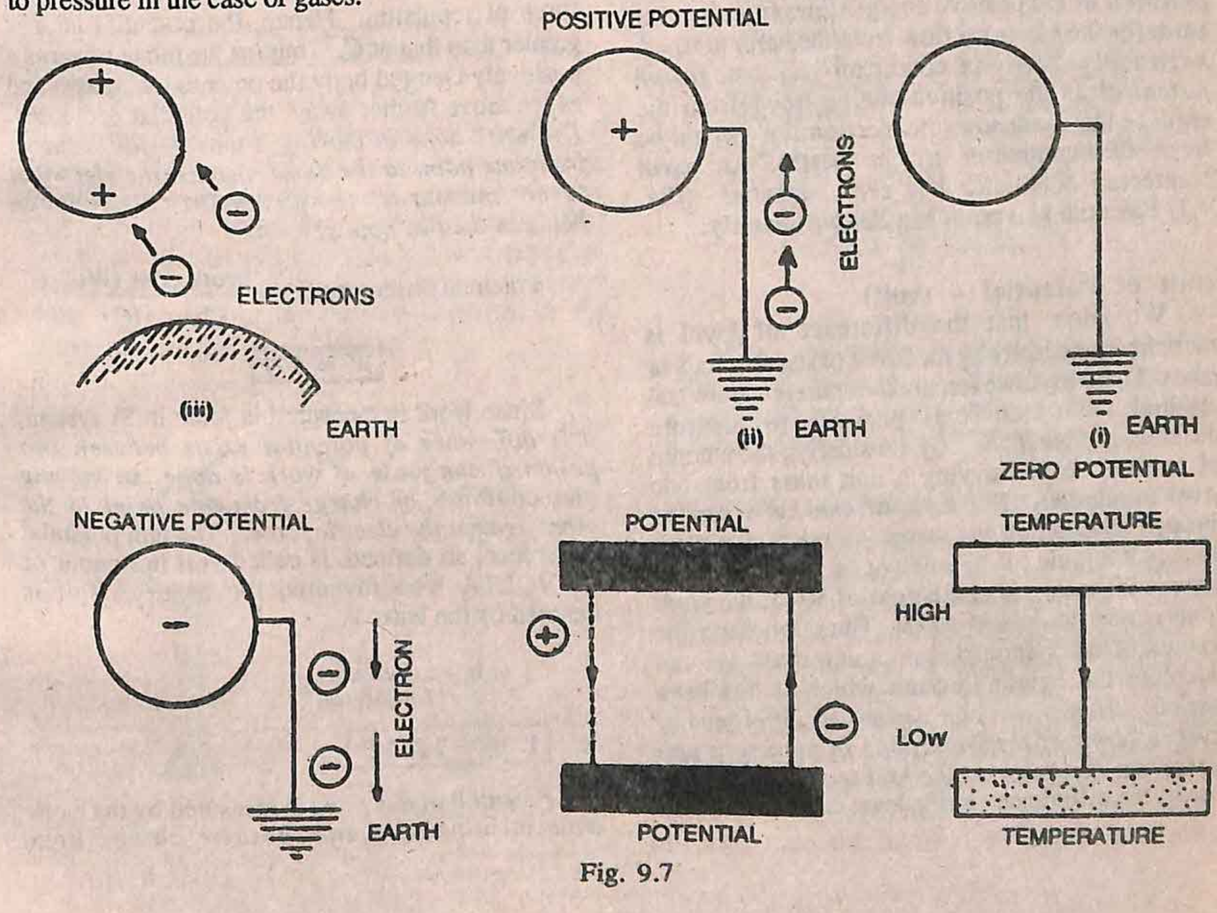


Fig. 9.7

to water only because the former is at a higher temperature. *There will be no flow of heat from either of them to the other if their temperatures are the same.*

Since temperature is the degree of hotness of a body so *electric potential may also be defined as the* **degree of electrification of a charged body.**

Just as the height of a place is measured with respect to sea-level which is taken as *zero* or *standard level* (as its capacity for water is so huge that any addition or removal of a small quantity of water does not affect its level appreciably), the potential of a conductor is measured with respect to that of the earth which is taken at **Zero potential.** Earth is a good conductor of electricity and a *huge capacity* for *electric charge* and any addition or removal of a small charge would not alter its potential appreciably.

The potential of a *positively* charged body is *above* the potential of the earth and potential of a *negatively* charged body is *below* that of the earth. Thus a positively charged conductor has a *positive potential* as the positive charge flows from it to the earth (or the electrons flow from the earth to it). A *negatively charged* conductor has a *negative potential* as the positive charge flows from the earth to the conductor (the electron flow would be from the conductor to the earth). An earth connected conductor has *zero potential* (Fig. 9.7) Potential at a point is a *Scalar* quantity.

Unit of Potential - (volt)

We know that the difference of level is measured practically by means of measuring rods or tapes. There is, however, another purely theoretical method by which it is possible to measure difference of level, *viz.*, by considering the amount of work done in carrying a unit mass from one level to another. If a mass of *one kg* is carried through a height of *one metre* vertically, the work done is 9.8 joule ; if to a height of 10 m, the work done is 98 joule ; if to a height of 50 m, the work done is 490 joule and so on. Thus, knowing the amount of work expended on a unit mass, we can calculate the height through which it has been carried. *Hence, we can define the difference of level in terms of the work done in moving a unit mass from the lower to the higher level.* In other words, the difference in the level can be measured by *the difference of gravitational potential energy* which the *unit mass* possesses at the two places. What is true of the level is also equally true of electric potential. In other words, *we can measure the electric potential difference between two points in terms of the work done in moving a unit positive charge from one point* to *another.*

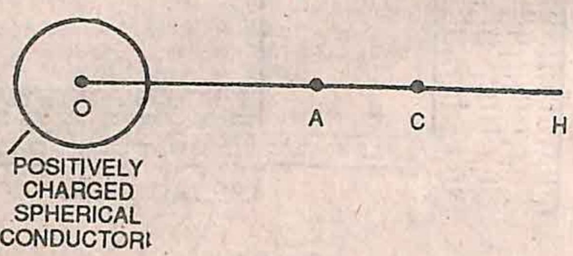


Fig. 9.8

Let us consider a spherical conductor, charged positively (Fig. 9.8) and let *A* and *C* be two points on the line *AH*. If a unit *positive charge be placed at C, it will experience a force of repulsion, tending to take it away from the sphere and so in moving it to A, work has to be done against this force of repulsion. Hence, the potential at *A* is greater than that at *C*. Thus, as we move towards a positively charged body the potential increases and as we move further away, the potential decreases. *The work done in moving a unit positive charge from one point to the other against the electrical force measures the* **potential difference** *between the two points.*

$$\text{Potential difference } (V) = \frac{\text{Work done } (W)}{\text{Charge } (Q)}$$

$$\boxed{W = VQ}$$

Since work is measured in *joule* in SI system, *unit difference of potential exists between two points if one* **joule** *of work is done in moving* **one coulomb** *of charge from one point to the other against the electric force.* The unit potential difference, so defined, is called **volt** in honour of *A.* VOLTA who invented the battery. Volt is denoted by the letter *V*.

$$1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$$

or $\boxed{1\ V = 1 J/1 C}$

Potential at any point is measured by the work done in bringing a *unit positive* charge from infinity to that point, against the electric force. Thus a volt is the potential at a point when one joule of work is done in bringing one coulomb of charge from *infinity* to that point.

One thousandth of a volt is called one *millivolt* (*mV*) and one millionth of a volt is called *micro-volt* (μV). One thousand volt is *kilovolt* (*k V*) and one million volt is *megavolt* (*MV*).

Thus

$$\boxed{\begin{array}{l} 1\,mV = \dfrac{1}{1000}V = 10^{-3}V \\ 1\,\mu V = 10^{-6}V = \dfrac{1}{1000000}V \\ 1\,kV = 10^{3}\,V \\ 1\,MV = 10^{6}\,V \end{array}}$$

Thus *electron volt* (*eV*), a widely used unit in atomic physics, is the energy acquired by an electron that has been accelerated by a potential difference of 1 volt.

$$\boxed{1\,eV = 1.6 \times 10^{-19}\text{ joule}}$$

9.8 ELECTRIC CURRENT

We have learnt about the transfer charge, that is, when two charged conductors at different electrical potential are joined (Fig. 9.9), positive electric charge will flow from the conductor at a higher potential to the conductor at a lower potential *(Electrons carrying a negative charge will flow from the conductor at a lower potential to the conductor at a higher potential*),

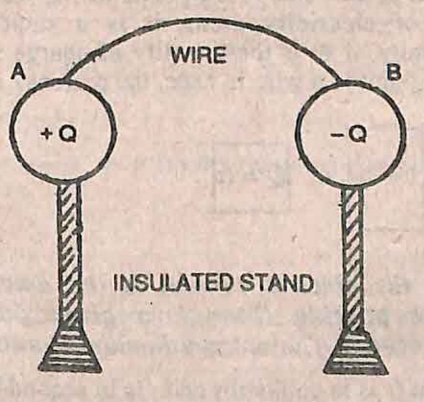


Fig. 9.9

Such an ordered (directional) flow of electric charge is called an electric current. *Thus an electric current flows when there is an electric potential difference.*

To keep an electric current flowing through a conductor, it is obviously necessary *to maintain the potential difference between its ends,* that is to maintain a difference in electrical energy level between the ends. This, of course, requires the expenditure of some other form of energy.

Taking again the hydrostatic analogy (Fig. 9.10), if a continuous current of water is to be obtained between the two vessels, their difference of levels must be maintained by pumping back water from the vessel in which it is at a lower level to the one in which its level is higher *at the same rate* at which it flows from the latter to the former (Fig. 9.10)

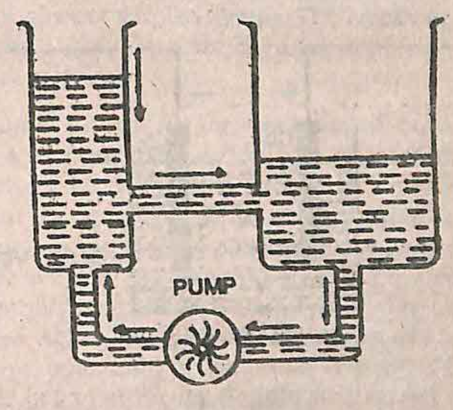


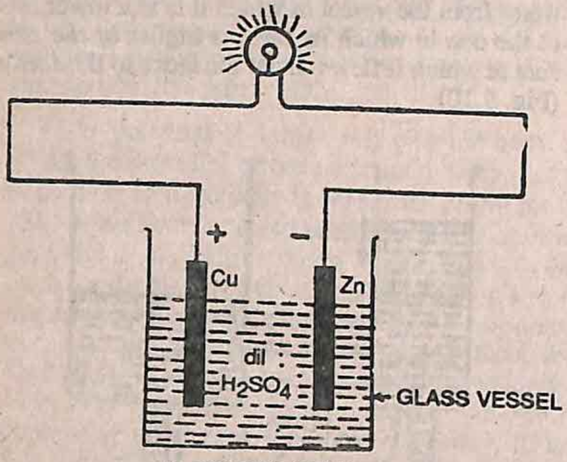
Fig. 9.10

When the pump is operating, it produces pressure differences between the various parts of the system and water flows from regions of higher pressure to regions of lower pressure.

SOURCE OF ELECTRIC CURRENT

The flow of charge round an electric circuit is similarly produced by differences in electrical pressures produced by the battery. Such a difference in electrical pressures is called the *potential difference*. In order that electric current should pass from one point in the circuit to another, the battery or any other electric source must maintain a potential difference between two points. Energy is required to keep the current moving round the circuit. The energy comes, of course, from the *battery* or *the source of steady* *current*. One of the earliest devices capable of providing a source of steady current was invented in 1800 by the Italian Physicist A-Volta. It is called a *voltaic cell*. Since then various kinds of *dry cells* and *storage batteries* have been devised. Dry cells are widely used in torches, transistor sets, tape recorders etc., and they are cheap and portable.

A voltaic cell consists of two plates, one of *copper* and the other of *zinc*, both dipped in a vessel containing *dilute sulphuric acid* and kept apart each other as shown in (Fig.9.11). When these plates are connected by a copper wire, *an electric current flows from copper to zinc outside the vessel and from zinc to copper inside it.* (Electrons move from zinc to copper outside the vessel). This shows that as zinc reacts with dilute sulphuric acid, the zinc plate gets negatively charged, while the copper gets positively charged. Thus *copper plate is at a higher potential than the zinc plate*. It will also be seen that when the plates are connected together, bubbles of hydrogen rise on the surface of the copper plate and zinc goes into solution forming zinc sulphate. *It is the energy liberated from this chemical action which maintains the current.* ***Hence the source of electricity in this case in the chemical action between zinc and sulphuric acid.*** In other words in this device, **chemical energy is changed into electrical energy. Such a device is called a *Primary cell***



(A VOLTAIC CELL)

Fig. 9.11

Electricity that we use in our homes is generated at a *power station.*

Unit of electric current :

The analogy between a continuous steady flow of water along a tube and continuous steady flow of electricity along a wire is a useful aid to understanding some of the principles concerning an electric current.

Consider a tube AB [Fig. 9.12 (a)] which has a continuous steady flow of water along it in the direction A to B. The *current* of water is the volume of water *per second* passing any section S, and if 25 m^3 pass S in 5 seconds, the current $= \frac{25}{5} = 5\ m^3s^{-1}$. **The time element is therefore, concerned in the idea of current.** From the water analogy, if 15 coulombs of electricity flow past the point T in the wire MN of [Fig. 9.12 (b) in 3 seconds, the electric current $= \frac{15}{3} = 5$ coulombs/second. The current is the same at all points of the wire if the flow of elecricity along it is a steady one. Generally, if Q is the quantity of charge flowing past a point in a wire in t sec, the current I is given by

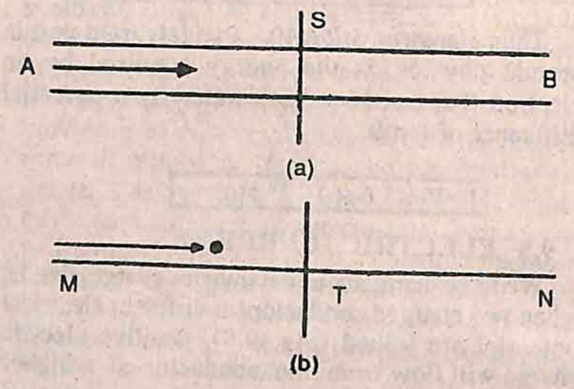


Fig. 9.12

$$\boxed{1 = \frac{Q}{t}} \text{ or } \boxed{Q = It}$$

Thus, ***the electric current is the amount of charge passing through a given point in one second.*** Current is a ***Scalar quantity.***

Where Q is in coulombs and t is in seconds, then I is in amperes. An ampere is the practical unit of current and is denoted by the letter A.

Thus 1 ampere = $\frac{1 \text{ coulomb}}{1 \text{ second}}$ and corresponds to a flow of 6.25×10^{18} electrons/second past a point.

Hence current is *one ampere* if a charge of *one coulomb* flows through any cross-section of the conductor in *one second.*

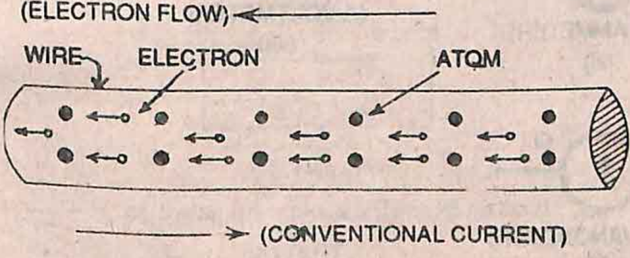
This, however does not mean that if there is a current of 1 ampere through a wire, 6.25×10^{18} electrons are actually flowing from one end of the wire to the other every second. It only means that there is a *drift* of so many electrons every second (not necessarily involving the same electrons) from one end of the wire to the other.

Sometimes, smaller units for measuring current are used. They are *milliampere (mA) and microampere* (μA).

$$1mA = \frac{1}{1000}A = 0.001A$$

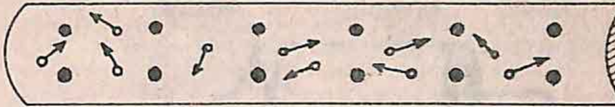
$$1\ \mu A = \frac{1}{1000000}A = 0.000001A$$

9.9 ELECTRON FLOW AND CONVENTIONAL CURRENT



(Electrons move in a specific direction towards the positive pole, when electricity is passed along the wire.)

Fig. (9.13)



(A random motion of electrons in a metal wire. Big filled circles are atoms and small circles are electrons.)

Fig. (9.14)

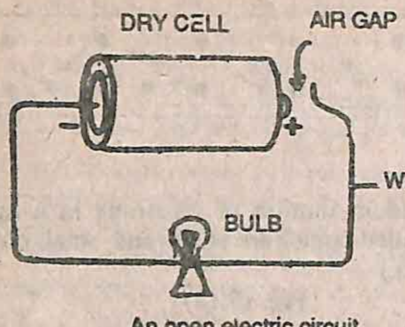
Inside a wire, electrons normally drift about in all directions between the atoms of the metal (Fig. 9.13). When the wire is connected to a source of electricity *e.g.*, a cell or a battery etc., the electrons begin to move in one direction and an electric current flows along the wire (Fig.9.14). In other words, the current in a closed circuit is the ordered flow of electrons in the circuit. The electrons from the source flow from its *negative* terminal to its *positive* terminal.

Conventionally, the direction of current is taken as the direction of flow of a *positive* charge. Therefore, in an electric circuit the direction of current is always taken as **opposite** to the direction of the flow of electrons. *Any point in the circuit which is at a higher potential for electrons is regarded as a lower potential for current, and is marked negative*. Similarly any point which is at a lower potential for electrons is regarded as a higher potential for the current in a circuit and is marked **positive.**

9.10 ELECTRIC CIRCUIT

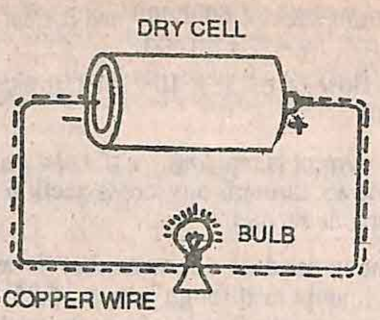
Electricity travels along a path. If the path is broken off, then electricity cannot travel. ***The whole path along which electricity travels is known as an electric circuit.*** An unbroken path travelled by electricity is known as a *closed circuit* (Fig. 9.16) and a broken path is known as an *open circuit*. (Fig. 9.15). **Electricity will not flow in an open circuit.**

Often it is useful to illustrate components in an electrical circuit by simple symbols. **A diagram which indicates how different components in a circuit have been connected, using conventional symbols for the components, is called a circuit diagram.**



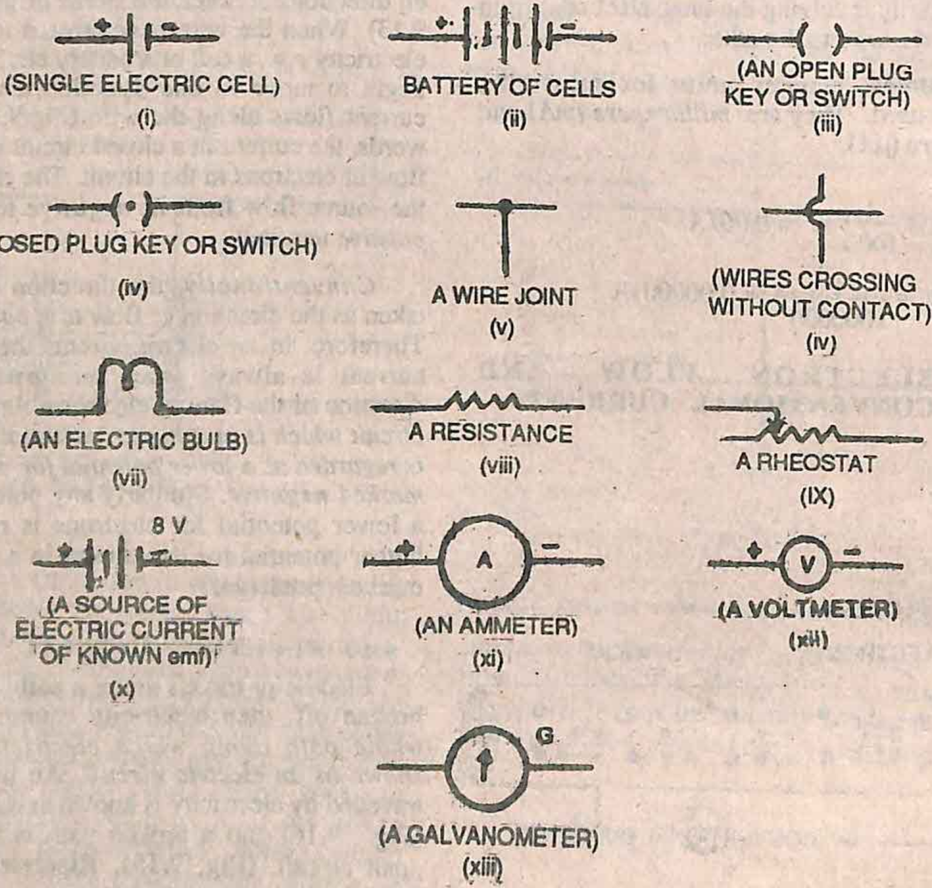
An open electric circuit

Fig. 9.15



An closed electric circuit.

Fig. 9.16



(SINGLE ELECTRIC CELL) (i)

BATTERY OF CELLS (ii)

(AN OPEN PLUG KEY OR SWITCH) (iii)

(A CLOSED PLUG KEY OR SWITCH) (iv)

A WIRE JOINT (v)

(WIRES CROSSING WITHOUT CONTACT) (iv)

(AN ELECTRIC BULB) (vii)

A RESISTANCE (viii)

A RHEOSTAT (IX)

(A SOURCE OF ELECTRIC CURRENT OF KNOWN emf) (x)

(AN AMMETER) (xi)

(A VOLTMETER) (xii)

(A GALVANOMETER) (xiii)

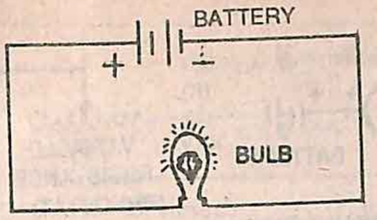
Fig .9.17 (*a*)

The conventional symbols for some common components of electric circuits are given in Fig. 9.17.

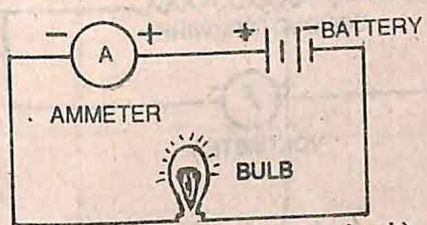
AMMETER :

Ammeter is a short name for ampere-meter which means an instrument designed to measure the current (flowing in a circuit) directly in amperes. As the current in the circuit is same every-where, *an ammeter may be placed anywhere in the circuit in series with it.*

The ammeter thus becomes an essential part of the circuit in which it is joined [Fig.9.17 (*b*)]. The ammeter must always be connected so that the current may enter it at the terminal marked + otherwise the pointer will tend to be deflected in the opposite direction beyond the zero of the scale and thus may get bent or broken.



(a) A simple electric Circuit

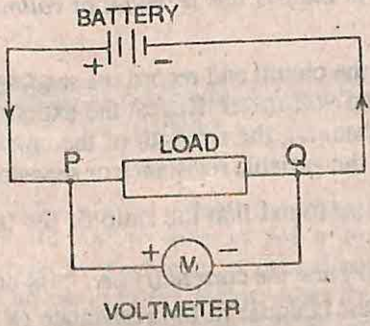


(An ammeter connected in the circuit)

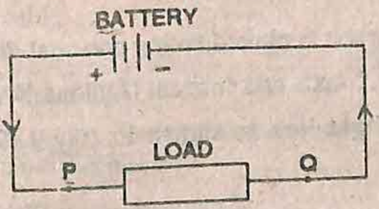
Fig. 9.17 (b)

VOLTMETER :

A voltmeter is an instrument used for measuring potential difference between two points. In order that the voltmeter should measure the potential difference between any two points (say *P and Q*), *it must be placed* **in parallel** *with the circuit* [Fig.9.17 (*c*)]. The voltmeter must be connected so that the current enters at the terminal marked +. In contrast to an ammeter, a voltmeter is joined *as an additional* to an already completed circuit. [Fig 9.17(*c*)].



(A Voltmeter connected in the circuit)



(Asimple electric circuit)

Fig. 9.17 (c)

Note the language used to describe the action of two metres. An ammeter measures current **through** a component, while a voltmeter measures potential difference across a component.

9.11 CURRENT-POTENTIAL DIFFERENCE RELATIONSHIP (Ohm's Law)

From the analogy between electric potential and water level, it would appear that there must be a definite relation between the potential difference applied to the two ends of a conductor and the magnitude of the electric current flowing in it. Such a relation was discovered experimentally by *George Simon Ohm* of Germany in the year 1827 in the form of what is known as ***Ohm's Law***. The law states :

"The ratio of the potential difference across the ends of a conductor to the current flowing through is constant so long as the physical conditions, i.e., temperature, density etc., of the conductor remain the same."

Suppose that a current of 4 amperes is flowing through an electric wire connected to the 240 volts main supply. What would the current be if the main voltage falls to 120 volts ? Ohm's Law tells us that since the potential difference (voltage) has been halved, the current will be reduced in the same proportion, *i.e.*, halved. The net current is, therefore, 2 amperes. If the voltage had dropped to 80 volts (*i.e.*, 1/3 of its original value) the current would drop proportionately 4/3 amperes, (*i.e.*, 1/3 of its original value). In each case,

$$\frac{\text{Potential Difference}}{\text{Current}} \text{ is the same } i.e..$$

$$\frac{240}{4} = 60 \,;\ \frac{120}{2} = 60 :\ \frac{80}{4/3} = 60$$

If V = Potential difference

and I = current, then

mathematically speaking, Ohm's Law can be stated as

$$\boxed{\frac{V}{I} = \text{constant}}$$

or $\boxed{\frac{V}{I} = \mathrm{R}}$ where R is a constant known as **resistance of a conductor.**

Ohm's Law is valid under definite conditions for metallic conductors. It fails for solutions, semiconductors and for gases.

Ohm's Law provides a basis for measuring the resistance.

9.12 RESISTANCE OF A CONDUCTOR

Whenever an electric current flows through a conductor, the conductor offers some opposition to the flow of the electric current. *This property of the conductor by virtue of which it opposes the flow of an electric current through it is called* **resistance** *of the conductor.*

According to Ohm's Law, resistance (R) is measured by the ratio of the potential difference (V) developed at the two ends of the conductor to the current (I) passed through it.

$$\text{Resistance } (R) = \frac{\text{Potential Difference } (V)}{\text{Current } (I)}$$

Resistance is measured in **ohms**. The symbol for ohm is Ω.

If a potential difference of 1 volt is developed across the two ends of a conductor when a current of 1 ampere flows through it, then the resistance of the conductor is said to be one ohm.

$$\text{Hence } \boxed{1 \text{ ohm} = \frac{1 \text{ volt}}{1 \text{ ampere}}}$$

The resistance of a conductor (pure metal) varies with the change in temperature. For an alloy like *manganin* (84% Cu ; 4% Ni and 12% Mn) or *constantan* (60% Cu and 40% Ni), there is extremely small change in resistance with change in temperature and hence it is for this reason that they are mostly used for making *standard resistances.*

A conductor possessing a certain resistance is usually called a *resistor.*

9.13 EXPERIMENTAL VERIFICATION OF OHM'S LAW

Set up a circuit as shown in (Fig. 9.18).

XY = a *eureka wire* about 100 cm long.

B = a *battery* of a number of cells which sends current round the circuit.

K = a *key* for making and breaking the circuit.

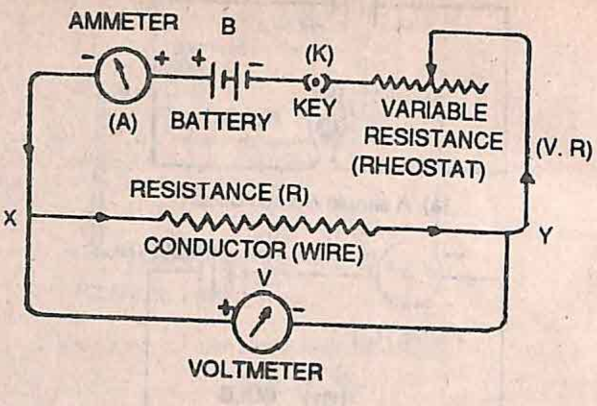


Fig. 9.18 Verification or Ohm's Law.

A = an *ammeter* which measures *I*, the strength of the current in *amperes.*

V = a *voltmeter* which measures, *V*, the potential difference between the ends of the wire in volts.

V.R. —*Variable resistance* or *Rheostat* for varying the strength of the current by changing the total resistance of the circuit.

The positive terminal of the battery should be connected to the positive terminal of voltmeter and ammeter.

Close the circuit and record the readings of the ammeter and volt-meter. Repeat the experiment six times by changing the strength of the current with the help of the variable resistance or rheostat.

It will be found that the ratio of the potential difference (V) and the current (I) *i.e.,* $\frac{V}{I}$ is constant. This constant is equal to the resistance (R) of the wire *XY*.

If a graph is plotted taking potential difference (V) along *X* -axis and currrent (I) along *Y*- axis, we get a straight ling as shown in (Fig.9.19) ; this means

$$V \propto I$$

It also verifies Ohm's law.

S.No	Potential Difference V (In volts)		Current I (in amperes)		$\frac{V}{I} = R$ (in ohms)
	Observed	Corrected	Observed	Corrected	
1.					
2.					
3.					
4.					
5.					
6.					

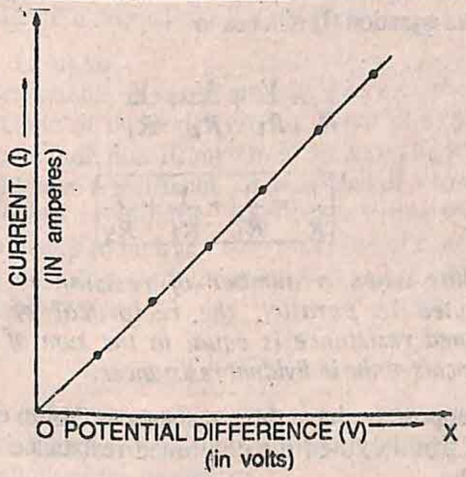


Fig. 9.19

Here it should be borne in mind that the current should not be passed for a long time otherwise heat is produced in the wire and that introduces an error in the result. Also the sliding contact of the variable resistance (V.R.) should be moved so as to increase the current by equal steps as far as possible.

9.14 COMBINATION OF RESISTANCES

There are two distinct ways in which the resistances can be connected :

(*i*) Resistances in series ; and

(*ii*) Resistances in Parallel.

Resistances in Series : In many applications of electrical circuits two or more resistances (or conductors) are often connected end to end, so that the current must flow first through one and then through the other. Such a connection is called a *series* connection. It is an important property of a series connection that the *same strength of current* flows through all parts of it.

The current does not get gradually used up as it flows around the circuit. In this respect, it is similar to the flow of water through a long pipe which has no side branches. The same volume of water per second must flow, at a given instant, through every cross-section of the pipe. If this were not so, then either the amount of water in the pipe would increase and burst the pipe or the amount of water in the pipe would decrease until the pipe was nearly empty.

Let R_1, R_2, R_3 be the resistances of the various conductors joined in series (Fig. 9.20) and I be the current flowing in them. If V_1, V_2 and V_3 be the potential differences developed across the ends of these conductors, the total potential difference (V) across the combination is given by

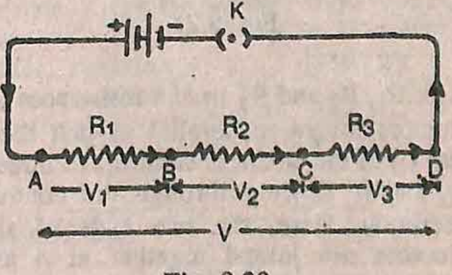


Fig. 9.20

$$V = V_1 + V_2, + V_3 \qquad \text{......(1)}$$

Now, by Ohm's law, we have

$V = IR$, where R = total resistance of the combination

$$\therefore V_1 = IR_1$$

$$V_2 = IR_2$$

and $V_3 = IR_3$ because the *same current* is flowing through all the conductors.

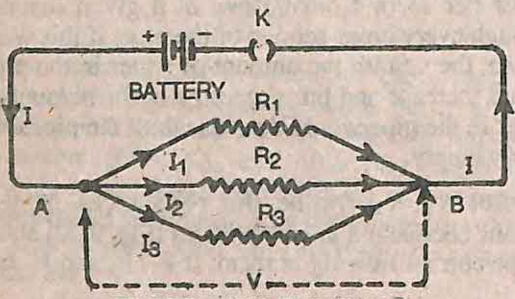
Substituting these values in the equation (1), we have

$$IR = IR_1 + IR_2 + IR_3$$

or $$\boxed{R = R_1 + R_2 + R_3} \qquad \text{.....(2)}$$

Thus the total resistance of the circuit is equal to the sum of the resistances of the individual conductors joined in series. The total resistance increases by such a combination of conductors.

(*ii*) **Resistances in Parallel.** When two or more resistances conductros are connected between two points so that the current *divides* between them and then rejoins, they are said to be *in parallel*. The circuit diagram for such a combination of resistances is shown in Fig. 9.21.



(RESISTANCES IN PARALLEL)

Fig. 9.21.

Let R_1, R_2 and R_3 be the resistances of the conductors joined in parallel so that the total current (I) of the circuit is divided into three parts I_1, I_2, and I_3 flowing through the conductors respectively. Here, the two ends of all the conductors are joined together at A and B. Therefore, the potential difference at the ends of each conductor is the same (say V).

Now the total current flowing in the combination is given by

$$I = I_1 + I_2 + I_3 \qquad \text{...(1)}$$

Applying Ohm's law, we have

$I = \frac{V}{R}$ where R = total resistance of the combination.

$$I_1 = \frac{V}{R_1}$$

$$I_2 = \frac{V}{R_2}$$

and $$I_3 = \frac{V}{R_3}$$

The equation (I) reduces to

$$\frac{V}{R} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

or $$\boxed{\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Thus when a number of resistances are connected in parallel, the reciprocal of the combined resistance is equal to the sum of the reciprocals of the individual resistances.

Suppose we have three resistances 2 ohm each put in parallel, then the combined resistance R is given by

$$\frac{1}{R} = \frac{1}{2} + \frac{1}{2} + \frac{1}{2} = \frac{3}{2}$$

$$R = \frac{2}{3} \text{ ohm} = 0{\cdot}66 \text{ ohm}$$

It is, thus, clear that the total resistance is less than the resistance of any single conductor.

Electric lamps are nearly always wired in parallel. Lamps wired in parallel have a smaller total effective resistance than the same number of lamps wired in series. Parallel connection of electric resistances is widely used in industry and household purposes.

9.15 FACTORS AFFECTING RESISTANCE (SPECIFIC RESISTANCE OR RESISTIVITY)

The various factors that affect the resistance of a conductor are :

(1) Temperature :

The resistance of all substances changes to some degree with changes in temperature. In the case of pure metals and most metallic alloys, *the resistance increases with a rise in temperature.* Carbon, semiconductors and many electrolytic solutions, on the other hand, show a *decrease in resistance* as their temperature is raised. A few special alloys, such as constantan and manganin, show *very slight changes in resistance* over a considerable range of temperatures. For practical purposes, the resistance of these alloys can be considered independent of temperature.

(2) Length

Resistances in series are added to give the total resistance of the series circuit. From this fact we can conclude that 10 meters of a certain conductor should have a resistance 10 times that of 1 meter of the same conductor. Experiments prove this relationship to be true ; *the resistance of a uniform conductor is directly proportional to the length of the conductor*

$$\boxed{R \propto l}$$

where R is the resistance of the conductor and l is the length of the conductor.

(3) Area of cross-section :

If three *equal* resistances are connected in an electric circuit, the equivalent resistance is one-third the resistance of any one branch. The equal currents in the three branches add to give the total current in the circuit.

Assuming the three resistances to be three similar wires 1 metre in length, each having a cross-sectional area of 0.1 cm^2, we can think of the equivalent resistance as a similar wire of the same length but having a cross-sectional area of $0.3 cm^2$. This deduction is reasonable, since a wire carrying a direct current of constant magnitude has a constant current density throughout its cross-sectional area. If the parallel resistances are designated R_1, R_2 and R_3 then

$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$ where R is the equivalent resistance. But $R_1 = R_2 = R_3$

So $\frac{1}{R} = \frac{3}{R_1}$

and $R_1 = 3R$

We can conclude that the resistance ot the large wire, R, is one-third the resistance of the small wire, R_1, and experiments prove this conclusion to be true. *The resistance of a uniform conductor is inversely proportional to its cross-sectional area.*

$\boxed{R \propto \frac{1}{A}}$ where A is the cross-sectional area of the conductor. In case of a wire, $A = \pi r^2$ where r is the radius of the wire.

(4) Nature of the Materials :

A copper wire having the same length and cross-sectional area as an iron wire offers about one-sixth the resistance to the flow of electricity. A similar silver wire presents even less resistance.

Thus the resistance of ;a given conductor depends on the material of which it is made.

*Taking these four faactors into account, several useful conclusions become apparent. For a uniform conductor of a given material and temperature, the resistance is directly proportional to the length and inversely proportional to the cross-sectional area *i.e.*,

$$R \propto \frac{l}{A}$$

or $$\boxed{R = \rho\frac{l}{A}}$$

where ρ is a constant of proportionality and its value depends upon the material of the wire and its temperature. This constant ρ is called the ***specific resistance** or **resistivity** of the material of the wire.

From the above equation .

$$\boxed{\rho = \frac{RA}{l}}$$

We find that if,

$l = 1$ m

$A = 1 m^2$

than $\boxed{\rho = R}$

Thus, the specific resistance (or resistivity) of the material of a wire is the resistance of a wire of length 1m and having a uniform cross-sectional area of 1 m^2 or it is the resistance offered by a cube of the material of side 1 m when current flows perpendicular to opposite faces.

Unit of specific resistance :

$$\text{Since } \rho = \frac{RA}{l}$$

$$\therefore \text{ Unit of } \rho = \frac{\text{Unit of resistance } (R) \times \text{Unit of cross-sectional area } (A)}{\text{Unit of length } (l)}$$

$$= \frac{\text{ohm} \times (\text{metre})^2}{(\text{metre})} = \textbf{ohm-metre}$$

Hence specific resistance ρ is measured in **ohm-metre or Ω m.**

Table 9.1

***Resistivity of Specific Resistance of some substances at 20°C**

Substance	*Specific Resistance (Ohm-m)*
Aluminium	$2{\cdot}36 \times 10^{-8}$
Carbon	3500×10^{-8}
Copper	$1{\cdot}62 \times 10^{-8}$
Constantan	49×10^{-8}
Germanium	2×10^{8}
Gold	$2{\cdot}04 \times 10^{-8}$
Iron	$9–13–10^{-8}$
Lead	$20{\cdot}4 \times 10^{-8}$
Mercury	94×10^{-8}
Nichrome	100×10^{-8}
Phosphorus	1×10^{12}
Platinum	$11{\cdot}1 \times 10^{-8}$
Silver	$1{\cdot}60 \times 10^{-8}$
Sulphur	1×10^{17}
Tungsten	$5{\cdot}0 \times 10^{-8}$
Diamond	$10^{2}–10^{3}$
Ebonite	$10^{15}–10^{17}$
Glass (Pyrex)	10^{14}
Mica	$10^{13}–10^{17}$
Paper (dry)	10^{12}
Water (distilled)	$10^{4}–10^{7}$
Silicon	$10^{3}–10^{6}$

The resistivities of various materials are listed in the Table 9.1 Note that the value of ρ is independent of the length and the area of cross-section of the wire. It depends only on the material of the wire. Thus, the specific resistance is a characteristic of the material. If the specific resistance of a material is known, the resistance of any other wire composed of the same material can be calculated.

The resistivity of most metallic conductors increases with temperature. In the case of insulators such as ebonite, glass, diamond, etc., resistivity is very high and does not change with temperature. In between the metallic conductors and insulators, we have semi-conductors, whose resistivities decrease with increasing temperature. Semiconductors are proving to be of great practical importance because of their marked change in conducting properties with temperature, impurtiy, concentration etc.

9.16 HEATING EFFECT OF ELECTRIC CURRENT (An electric circuit transfers energy):

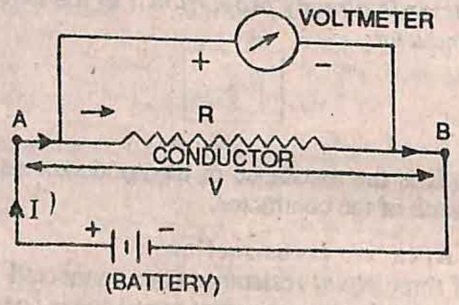


Fig. 9.22

Consider Fig. (9.22) in which a current (I) of electricity flows from *A* to *B* when the conductor (or the resistance wire) is connected to the terminals of a battery. The electric potential at *A* is greater than that at *B*. Since electricity in the wire is due to the steady drift of electrons, so the electrons moving under the influence of a potential difference between the ends of the conductor, must possess energy and this is called **electrical energy.** The fact that a conductor offers resistance to the flow of current implies that work must be done continuously to maintain a current. The role of resistance in electrical circuits is analogous to that of friction in mechanics. We know that if work is done when an electric charge is moved from one point to another in an electrical circuit, then a potential difference exists between the two points.

---

* For further knowledge only Not to be tested.

The amount of work done is a measure of a potential difference. The greater the work done, the bigger is the potential difference.

The unit of the potential difference is the **volt** which is defined as follows :

The potential difference between two points A and B is one volt if *one joule* of energy is released when a charge of *one coulomb* moves from point A to the other point B.

If the potential differaence between two ends of the conductor A and B were 2 volts, then 2 joules of energy would be released when one coulomb of charge is moved from point A to the other point B. So, if the potential difference between the two points A and B as shown by the Voltmeter is 'V' volts, the electrical energy liberated when a charge of one coulomb moves from point A to point B will be *V joules*.

Similarly, if *three coulomb* charge is moved between the two points A and B of the conductor whose potential difference is *one volt*, then the energy released would amount to *three joules*. So, when 'Q' coulombs of charge flow between the same potential difference (*i.e.*, 1 volt), energy released will be *Q joules*.

Hence, we may conclude that the energy liberated (as heat or otherwise) when Q coulombs of electricity move between two points having potential difference 'V' is given by--

$$\boxed{W\ (joules) = Q\ (coulombs) \times V\ (volts)}$$

or Work done by the electric current = Amount of electric charge moved × Potential difference between two points

Recollecting the relation between charge and electric current, we know that the electric current is the quantity of charge flowing through the conductor per unit time.

The unit of current is called the *ampere and is equivalent to flow of one coulomb of electricity per second through a conductor.*

Thus, if a current of I amperes flows in a conductor for t seconds, the total quantity of electricity which passes along it is given by :

$$Q\ (coulomb) = I\ (amperes) \times t\ (seconds)$$

Hence the work done by the current or the energy released is equal to

$$W\ (joules) = Q\ (coulomb)\ \times V\ (volts)$$

$$= I\ \text{(amperes)}\ \times\ t\ \text{(seconds)} \times V\ \text{(volts)}$$

or $\boxed{W = \text{V.I.}t\ \text{joules}}$

or $\boxed{W = I^2Rt}$

as $V = IR$ by ohm's law

The above formulas are used in practice to calculate electrical energy or work done by an electric current. All the quantities in the formulas are easily measured.

This shows that the energy dissipated is the product of the square of the current, the resistance R and time t. This energy appears mostly as heat, but sometimes also as light. *In the case of heaters, electric irons, radiators; toasters, etc; electrical energy is mostly converted into heat.* In the case of *electric lamps* about 5% only of the electrical energy is converted into visible light.

Let us suppose that all the electrical energy dissipated in the conductor appears as heat. Then, since, one calorie of heat is equivalent to 4·18 joule, the amount of heat (H) generated can be obtained by using equation

$$W = I^2Rt = VIt$$

and is given by

$$H = I^2Rt = VIt\ \text{joule}$$

or $$H = \frac{I^2Rt}{4{\cdot}18}\ \text{cal}$$

$$= \frac{VIt}{4{\cdot}18}\ \text{cal}$$

9.17 ELECTRICAL POWER

Power is defined as the amount of work done per unit time. It involves the time, t, in which a particular amount of work is done or energy is liberated.

Thus P = Work done (or energy liberated) per second

$$= \frac{W}{t}$$

In mechanics, the unit of power is *joule/second*

Thus, in electricity, the electrical power

$$P = \frac{W}{t} = \frac{QV}{t} \text{ joules/second}$$

$$\frac{IV.t}{t} = IV. \text{ joules/second}$$

A rate of working equal to one joule/second is called a **watt**, the unit of electrical power.

We, therefore, obtain the important expression

$$\boxed{P = I.V. \text{ watts}} \quad \text{....}(ii)$$

Since $I = \frac{V}{R}$ by Ohm's Law for the conductor, the power is also given by

$$P = I \times (I \times R) = I^2 R \text{ watts} \quad \text{....}(iii)$$

$$\text{and also } R = \frac{V}{R} \times V = \frac{V^2}{R} \text{ watts} \quad \text{....}(iv)$$

watt is a very small unit of electrical power. So in practice we use bigger unit of power. A large unit of power in common use is the *kilowatt.*

1 kilowatt (kW) = 1000 watt (W)

9.18 WORK DONE BY A CURRENT IN TERMS OF POWER AND TIME (ELECTRIC ENERGY) :

You know that power P is given as

$$P = \frac{W}{t}$$

$$\text{So,} \quad W = P \times t \quad \text{...}(v)$$

From equation (v), you can calculate the work done by electric current in terms of power and time.

Thus $\boxed{W\ (joules) = P\ (watts) \times t\ (seconds)}$

The joule or **watt second** is too small a unit for conveniently measuring large quantities of electrical energy. The *unit* of energy commonly used is the **kilowatt-hour(KWh)**. The domestic electricity meter measures the amount of electrical energy consumed in the home in terms of this unit.

The kilowatt-hour is the amount of energy consumed in one hour, when the power or rate of doing work is one kilowatt.

$\therefore$ 1 kilowatt-hour = 1000 watt for 1 hour

= 1000 watt for 3600 seconds

= 1000 joule/second for 3600 seconds

= 3600000 joule = $3{\cdot}6 \times 10^6$ J

If the rate consumption of energy in kilowatts is given, the number of kilowatt-hours used in a certain time is give by

Number of Kilowaatt, hours

of kilowatt × No. of hours = No.

$$= \frac{\text{No. of watts}}{1000} \times \text{No. of hours}$$

$$= \frac{\text{Volts} \times \text{amperes} \times \text{hours}}{1000}$$

The students should carefully note that *watt or kilowatt* is the unit of *power* and **kilowatt-hour** or **watt-hour** is the unit of the *electrical energy.*

9.19 ELECTRIC APPLIANCES BASED ON HEATING EFFECT OF CURRENT

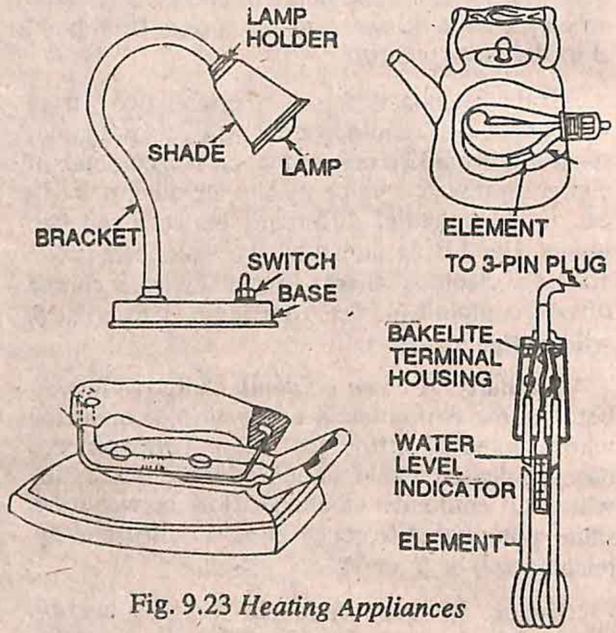


Fig. 9.23 *Heating Appliances*

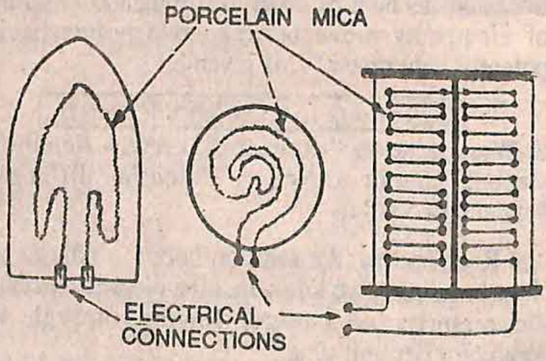
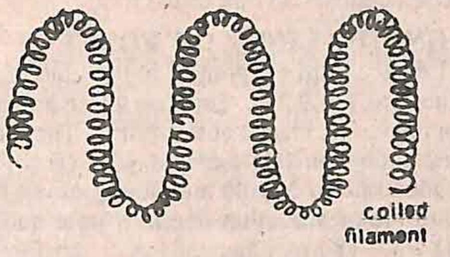
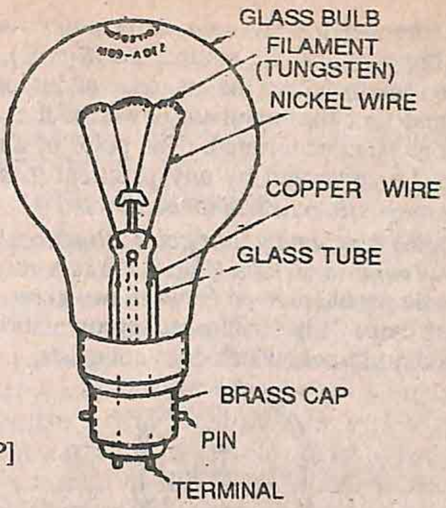


Fig. 9.24 *Heating Elements*

Many of the heating appliances that are used in the average home (common examples) are electric radiators, kettles, toasters, jugs, stoves, Electric iron, water heaters etc.





[FILAMENT LAMP]
Fig. 9.25

All of these devices make use of the heating effect of an electric current. In each case, a heating element (Fig. 9.24) is used. The element wire is usually composed of nichrome (an alloy of nickel and chromium) which has a very high melting temperature. As a rule, the wire is of such a size that the heat developed will not raise the temperature higher than red hot. The element is supported on a form made from some heat-resistant insulator, such as mica or porcelain.

The element of the radiant heater in composed of inconel which gives off invisible infra red radiation. This warms objects that it touches, thus being only suitable for personal heat. The element is put in a frame with a polished reflector to beam the heat into the room.

In industry, the heating effect of a current is also utilised for smelting metals and also in electric welding. In agriculture too, it is used for fodder-steamers, hay drying, incubators, etc.

Electric Filament Lamps

The first incandescent electric lamps were made by Edison in 1879. These had a filament of carbonised bamboo fibre, sealed into an evacuated glass bulb. When a suitable current was passed through the filament, it was heated to incandescence and emitted a yellowish light. These lamps were not very efficient and had a very limited life.

Tungsten filaments were first used in about 1910. These could be heated to a higher temperature and so gave more light for a given amount of electrical energy. In the modern incandescent lamp the filament consists of a very fine tungsten wire made into a closely coiled spiral, which is then contained in a glass bulb filled with an inert gas, usually argon or nitrogen.

The filament is heated by the electric current to a temperature of about 2500°C. The gas present tends to reduce the vaporization of the metal of the filament. This allows the filament to be operated at a higher temperature with a consequent increase in efficiency (*i.e.*, it uses less electrical energy for a given amount of light radiated).

9.20 ELECTROMAGNETISM : Electricity Produces Magnetism (Magnetic effects of Electric Current) :

Before we discuss the magnetic effects of electric current,we must *revise* a few basic facts about the concept of the magnetic field and magnetic lines of force which you learnt in your previous class.

Magnet :

Any material which possesses the following properties is said to be a *magnet*.

(i) When the material is dipped in iron filings the filings cling to it like whiskers, particularly in two places, and
(ii) When the material is suspended so that it can rotate freely in a horizontal place, it will always settle down in a particular direction *i.e.* towards north and south at a place.

Loadstone, which is found to occur in nature, possesses the above mentioned properties, is known as a *natural magnet*. If we can induce the above mentioned properties in a material by artificial means, magnets obtained in this manner are known as *artificial magnets*.

A magnet has two *magnetic poles* — north pole (N-pole) and the south pole (S-pole). These are the regions where the magnetic attraction is the strongest *i.e.*, the magnetic power of the magnet seems to be concentrated. The poles of a magnet cannot be separated by any practical means. *A single magnetic pole cannot be isolated.*

Like poles repel and unlike poles attract each other.

A *compass meedle* (Fig. 9.26) is a very small magnetic needle pivoted between two glass discs in a brass case. It is the closest approximation to an isolated north pole which does not exists.

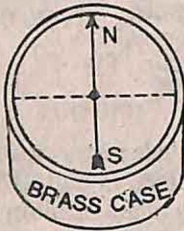


Fig. 9.26 (*Compass Needle*)

MAGNETIC FIELD :

It has been seen that a magnet attracts pieces of iron or steel even when they are lying at a certain distance away from it. A compass needle also placed at such a point is influenced by the magnet, although nothing happens in the space between the magnet and the needle. A screen of wood, glass or and other non-magnetic material will not obstruct the working of the magnet. The influence is mysterious and similar to that of gravity. The idea of a force "*acting at a distance*" can be easily understood by introducing the concept of a field. *The whole space all around a magnet in which the influence of the magnet (attraction, repulsion and induction) can be felt is known as* **the magnetic field** *or the field of the magnet.* The extent of this influence depends upon the strength of the magnet and the sensitiveness of the apparatus used for detecting this influence. The main property of a magnet by which we measure the extent of this influence at a given point is the force of attraction or repulsion experienced by another magnet placed there. As this force depends upon the pole strength of the magnet placed at the given point, it is customary to suppose that north-pole (*hypothetical northpole*) of *unit strength* is placed there. (Just as we considered a test charge in the case of an electric field). Hence we define the **Magnetic field intensity** *at a given point near a magnet as the force experienced by a hypothetical north pole of unit strength placed at that point (provided the presence of the pole does not disturb the field); the direction of this force gives the direction of the field.*

A hypothetical south pole will move in a direction opposite to that of the field.

MAGNETIC LINES OF FORCE

Let us consider a point *P* in the field of the bar magnet *NS* (Fig 9.27). Suppose a free and isolated north pole to be placed at this point. There are two forces acting on this isolated pole (*i*) a force of repulsion due to *N*-pole and acting along *NP* and (*ii*) a force of attraction due to *S*-pole and acting along *PS*. The resultant of these two forces will act along, say, *PP'*. If the free, isolated pole is now placed at *R*, there will again be two forces acting on it. These two forces differ in magnitude as well as in the direction from those acting at *P* and therefore their resultant will be acting in different direction, say *RR'*. Thus if a free and isolated north pole is placed in the field of a magnet, it will be moving along a curved path starting from the *N*-pole and terminating at the S-pole of the magnet. *The path* (straight or curved) *along which a free isolated north pole would travel in a magnetic field is called a* ***magnetic line of force***. It may also be defined as *a curve, a tangent to which at any point gives the direction of the resultant field at that point.* Generally we refer to an isolated north pole, but the path of an isolated south pole would be similar but in the opposite direction. The direction of the movement of a *north pole* is taken as the *positive direction* of the line of force.

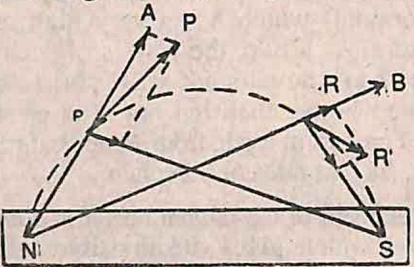


Fig. 9.27

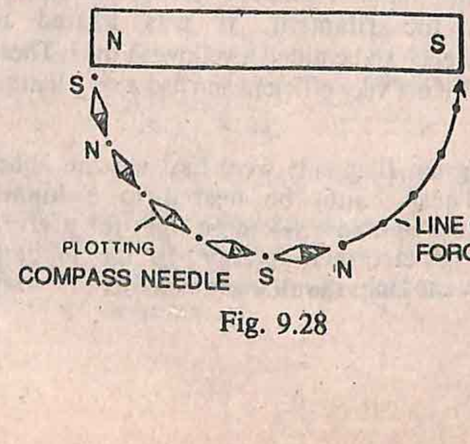


Fig. 9.28

In practice it is not possible to obtain a single pole but we can use a small compass needle for tracing the lines of forces (Fig. 9.28). This needle will come to rest along a line of force. Instead of using a compass needle, it is much simpler to use iron filings to show the direction of lines of force. Each small piece of iron is magnetised by induction and behaves like a small magnet.

From each point of the north pole, one line of force starts and passing through space it terminates on a corresponding fixed point on the south pole and from the south pole it travels through the body of the magnet and ultimately returns to the starting point on the north pole.

Properties of Magnetic Lines of Force :

The following properties are attributed by Faraday to the magnetic lines of force :

(i) They are *closed* curves.

(ii) They *start* from the *north pole* and after travelling in air *end* on *south pole* and then continue through the body of the magnet to the north pole again. Inside the magnet they are known as *lines of induction.*

(iii) They never intersect one another as, at one point (the point of intersection) there cannot be two directions of the resultant magnetic field.

(iv) They behave like stretched, elastic threads and tend to decrease in length (Longitudinal contraction). They repel each other sideways (Lateral repulsion).

(v) They start from a surface *normally* and also end at the surface normally.

(vi) The lines of force are connected at the poles ; thus the number of these lines of force per unit area is a measure of the field intensity at a point in that area. When lines of force come closer together, it indicates a stronger magnetic field and vice-versa.

(vii) There are no lines of force inside an iron ring as they tend to pass through iron rather than through air.

While the magnetic lines of force may seem to the beginners to be *quite imaginary,* we shall find later on that they are very useful in explaining the various electrical and magnetic phenomena.

Lines of force have no real existence, they are merely graphical representation of the magnitude and direction of magnetic force at any point in the field. These properties attributed to the lines of force can be utilized to explain ordinary phenomena like Induction, Attraction and Repulsion.

MAGNETIC EFFECT OF ELECTRIC CURRENT :

(Oersted's Experiment) :

The first discovery of any connection between electricity and magnetism was made by Hans Christian Oersted (1777-1851), Danish Scientist in 1820. Often during his lectures, at the university of Copenhagen. Oersted had demonstrated the non-existence of a connection between electricity and magnetism. His usual custom was to place a current-carrying wire at right angles to and directly over compass needle to show that there was no effect of one on the other. On one occasion at the end of his lecture, when several of the audience came up to meet him at the lecture room desk, he placed the wire parallel to the compass needle and not the least expecting it, saw the needle move to one side. Thus this great discovery was made quite by accident, but, such accidents come only to those who deserve them. Thus magnets are not the only sources of magnetic fields. Oersted *discovered that a wire carrying current behaves like a magnet or a current in a wire was capable of generating a magnetic field.* We now know from many other types of experiments that this is indeed the case. Further, more, *there are indications that the magnetic field of a magnet may also be the result of the motion of charges.*

When the current flows through a wire, there is no net charge on the wire—the number of electrons entering at one end is equal to the number of electrons leaving the other end. Hence, there is no net electric field around the wire. It is only *a moving charge that produces a magnetic field.*

Oersted placed a compass needle *NS* (Fig 9.29) on the table and held a wire *PQ* over this needle. On passing current in the wire found that

(i) the N-pole is deflected towards the west when the current flows from *S* to *N i.e. P* to *Q* [Fig.9.29 (a)].

(ii) the *N*-pole is deflected towards the east when the current is reversed [Fig.9.29(b)].

(iii) the deflection is reversed when the wire is placed *below* the needle.

(iv) there is no deflection of the needle if there is no current flowing in the wire.

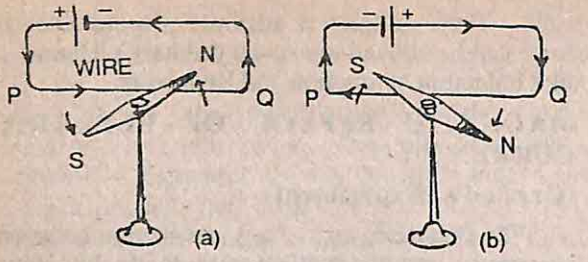


Fig. 9.29 *The deflection of a magnetic needle under the influence of an electric current.*

It follows from this experiment that whenever current is passed through a conductor, it produces a magnetic field around it. The *direction* of this magnetic field is given by **Ampere's Swimming Man Rule** stated below :

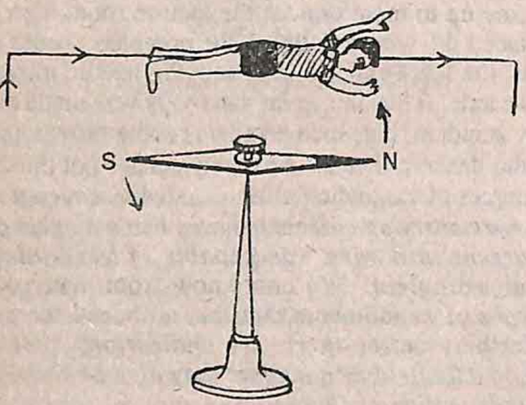


Fig. 9.30 *Swimming rule*

"Suppose yourself to be swimming along the conductor carrying current, so that the current enters at your feet (Fig.9.30) and leaves at your head and you are looking at the needle, the north pole of the needle will be deflected towards your left."

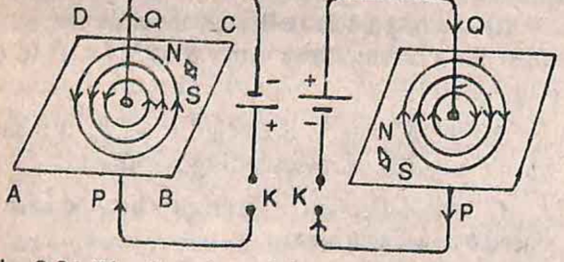


Fig. 9.31 *The direction of the magnetic field round a straight conductor carrying current.*

Ampere's rule may be remembered by the word **SNOW** which means that if the currents flow from South to North and the wire is over the needle, the north pole is deflected towards West.

MAGNETIC FIELD DUE TO A STRAIGHT CONDUCTOR (ARAGO'S EXPERIMENT) :

Arago took a card-board piece *ABCD* and fixed it horizontally and passed a thick copper wire *PQ* vertically through the board (Fig 9.31). A strong electric current was passed through this wire following from *P* to *Q* [Fig.9.31 (a)] and iron filings were sprinkled on the card-board and the card-board was then gently tapped. The filings arranged themselves in concentric circles with their common centre at *O* where the wire passes through the card-board. These iron filings arranged themselves along the magnetic lines of force round the conductor. The *N*-pole of a magnetic needle placed anywhere near the conductor tends to move in the anticlockwise direction.

If, however, the direction of the current is reversed [Fig.9.31(b)], the north pole begins to point in the clockwise direction.

Maxwell's Right–Hand Rule :

Arago's experiment also clearly shows that an electric current is always associated with a magnetic field. The direction of this field is given by the **Maxwell Right Hand Rule** stated on next page

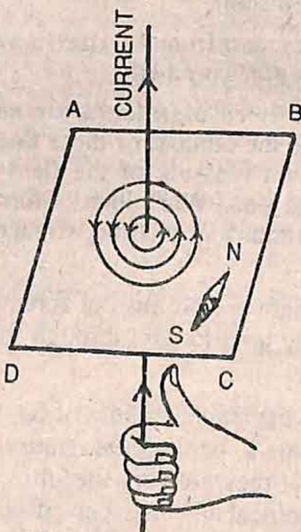


Fig. 9.32 *Maxwell's Right hand rule for determing the direction of the field round a conductor carrying current.*

"Hold the thumb of your right-hand at right angles to the fingers. Grasp the wire carrying current in the right-hand so that the thumb points along the wire in the direction of the current ; the fingers will then point in the direction of the magnetic field i.e., in the direction in which the north pole will be defleced."

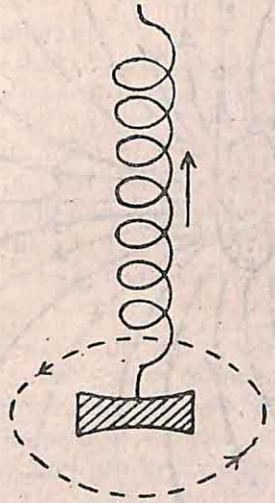


Fig. 9.33 *Cork Screw Rule.*

The direction of the magnetic field around a conductor can also be determined with the help of the **Cork-Screw Rule** in the following way :

"Imagine an ordinary right-hand cork screw to be lying with its direction coinciding with the conductor carrying current and to be twisted so that it travels in the direction of the current, then the direction in which the thumb rotates gives the direction of the lines of force (Fig. 9.33) *i.e., the direction in which the north pole tends to move round the wire.*

FIELD PATTERN DUE TO A CIRCULAR-COIL CARRYING CURRENT :

Take a sheet of card-board *ABCD* and make two holes (*P* and *Q*) in it a little apart from each other. Pass a thick stout copper wire through these holes bent in the forms of a circular loop as shown in Fig. 9.34. Hold the card-board horizontally, so that the coil is in the vertical plane and sprinkle iron filings upon it. Pass a strong current through the copper wire and tap the sheet a little. The iron filings are seen to adjust themselves along the directions of the magnetic field due to the current in the coil. At points where the wire passes through the sheet, the lines of force are almost circular, their direction being given by the *right hand rule.*

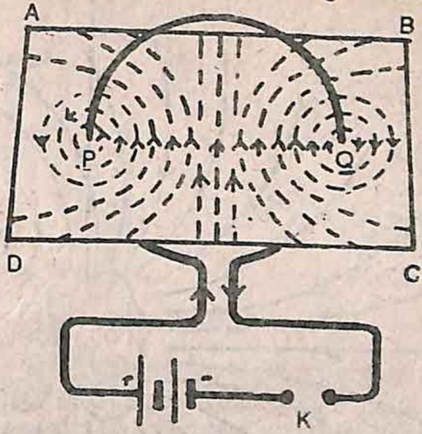


Fig. 9.34 *The magnetic field round a circular coil of wire*

It will be noted that the field at the centre of the circular coil is *away* from the observer and perpendicular to the plane of the coil. The lines of force at the *centre* are practically straight showing that the magnetic field due to the current in the coil is *practically uniform.* If the current is reversed *i.e.*, anticlockwise, the field will be *towards* the observer.

With the help of **clock rule** the polarity of any face of the coil can be determined. *If the current round any face of the coil flows in an* **anti-clockwise direction,** *it behaves like a* **north pole.** Similarly, if the current flows in the *clockwise direction*, the face acts like a **south pole.**

MAGNETIC FIELD DUE TO A SOLENOID :

A long coil of wire is called a solenoid. The magnetic field due to current flowing in a Solenoid is shown in Fig.9.35.

It is even more obvious here that the field is identical with that of a bar magnet. Such a solenoid (when a current is flowing through it), if suspended freely, will set itself along *N* and *S* like a compass needle. The ends of the current-bearing solenoid are attracted or repelled by a bar magnet.

An important difference between a current bearing solenoid and a bar magnet is that the solenoid is hollow and has an intense magnetic field along its axis, while a magnet is solid. It

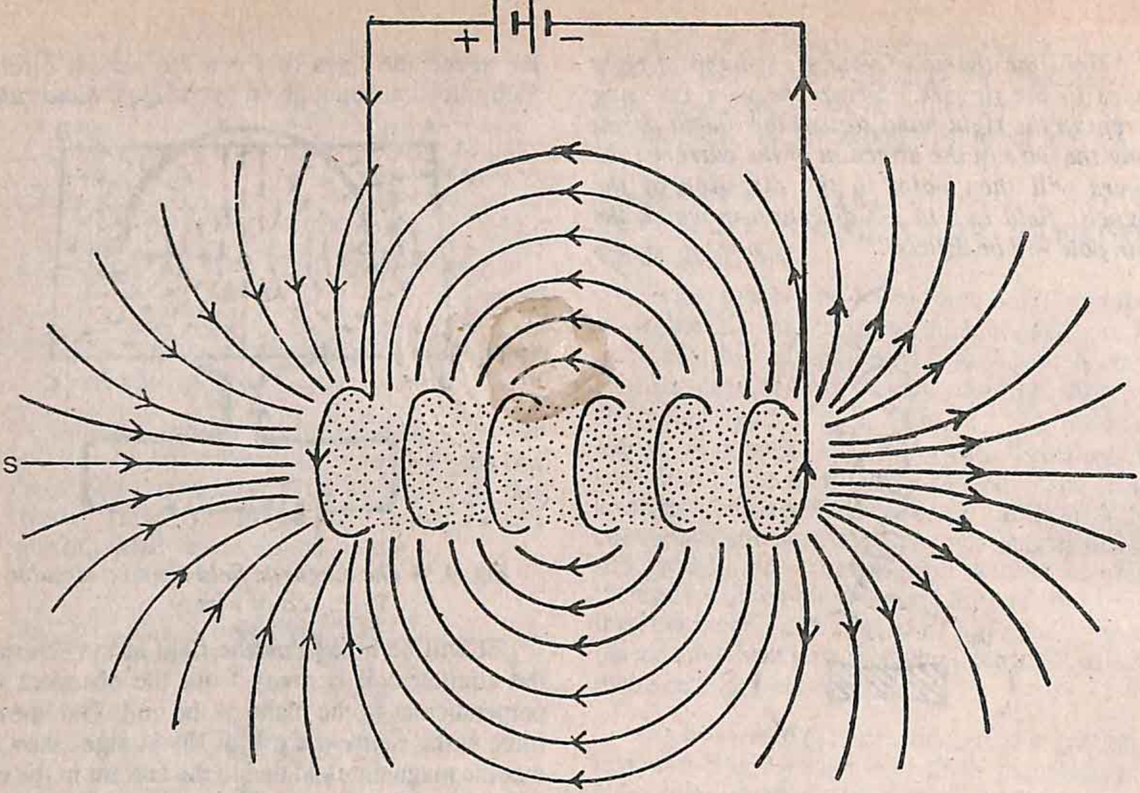


Fig.9.35 *Field due to a solenoid*

should be noted that in Fig.9.35 the lines of force inside the solenoid run for the end of south polarity to the end of north polarity. The positive direction of the magnetic field inside a solenoid is from the south end of the north end.

Students Activity :

Arrange the device as shown in Fig. 9 .36 Here the turns of the solenoid are passed through the top of the cardboard table.

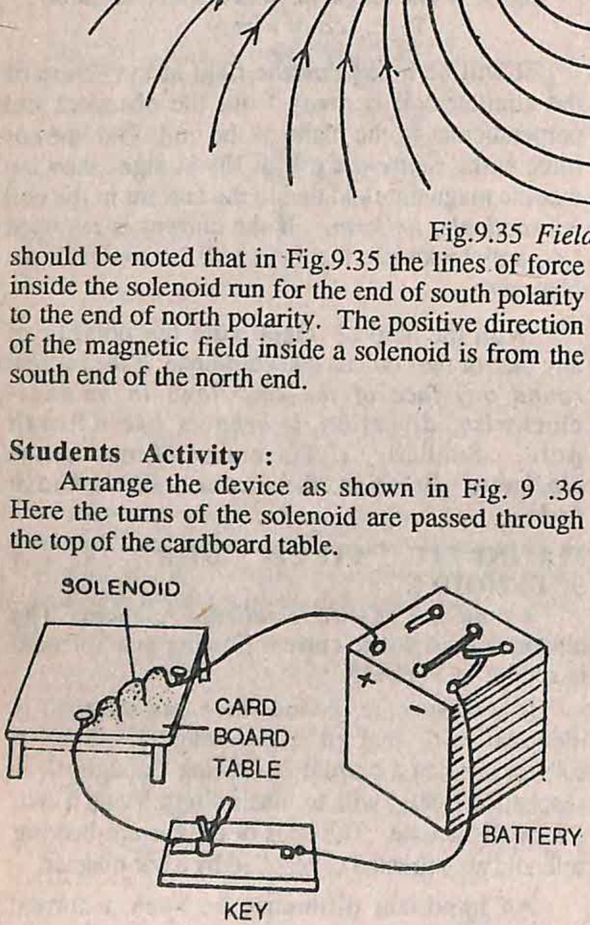


Fig. 9.36

Spread some iron filings on the cardboard. Connect the solenoid to the batterry of dry cells and tap the table gently. What do you observe ? How do the iron filings arrange inside the solenoid ? What does the distribution of magnetic lines of force demonstrate ?

Determine the poles of the coil with the help of a magnetized needle. From which pole do the magnetic lines of the force emerge ?

Magnetizing Action of a Solenoid

If a bar of iron is placed inside a solenoid carrying a strong current it becomes magnetized. The end of the bar at the end of north polarity of the solenoid acquires a North pole and the other end a South pole. This is a much quicker and more effective method of magnetizing than stroking with a bar magnet. The direction of magnetization clearly depends on the direction of the current and the way the solenoid is wound (Fig. 9.37).

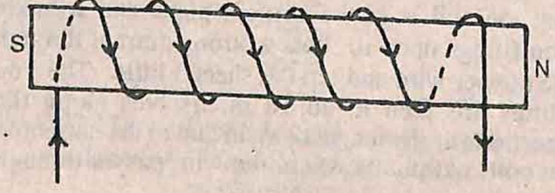


Fig. 9.37

To sum up the properties of a current-carrying solenoid.

(i) Outside it resembles a bar magnet.

(ii) Inside it has a strong magnetic field from south end to north end ; hence it is valuable for magnetizing.

The Electromagnet :

We have seen that a solenoid carrying current behaves like a magnet. If a bar of iron is inserted in the solenoid, the strength of the magnet is much increased, since the lines of force due to the magnetized iron are added to those due to the current in the solenoid. Such an arrangement (*i.e.*, solenoid with an iron core) is called an *electromagnet*. It was invented by Sturgeon in 1825.

The *strength* of the electro-magnet is proportional to the product of the strength of the current in amperes and the number of turns per centimeter. This product is often called the *ampere-turns*. If many turns of wire are used, weak current will produce as strong a magnet as a stronger current flowing through fewer turns.

When we compare the effectiveness of steel and soft iron core in an electromagnet, we see that the field is stronger in the case of soft iron core. But steel retains a small amount of magnetism even when the current has ceased to flow in the coil of the electromagnet, whereas in the case of soft iron core the magnetism disappears altogether as soon as the current ceases to flow in the coil of the electromagnet.

Make a coil of 30 turns of an insulated copper wire around a large iron nail. This will be our electromagnet. Connect the ends of the electromagnet to a storage battery through an ammeter and a rheostat as shown in Fig. 9.38. Bring some paper clips near one end of the electromagnet. Switch on the current and adjust it to a strength of 1 ampere with the help of the rheostat. What do you observe ? Count the number of paper clips attracted to the end of the electromagnet.

Repeat the experiment with a coil of 60 turns of the same copper wire over the same nail. Adjust the current to 1 ampere and find out how many of the clips are attracted this time ?

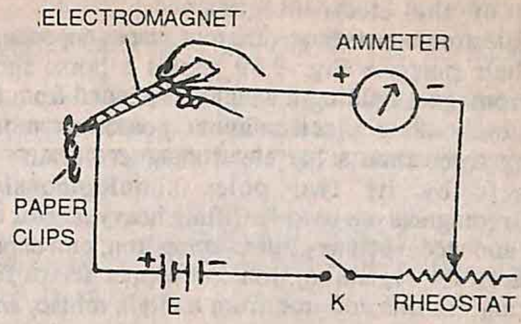


Fig. 9.38

Do we conclude that the strength of the magnetic field of the electromagnet increases with the increase in the number of turns of the coil provided the current is kept constant ?

Now repeat the experiment with an electromagnet of 30 turns. Adjust the strength of the current to 2 amperes. Find out the number of clips attracted to the electromagnet. What do you conclude ?

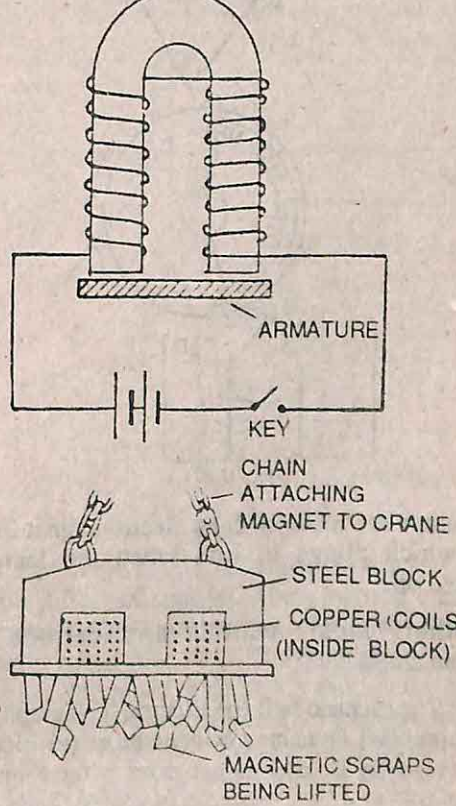

ARMATURE
KEY
CHAIN ATTACHING MAGNET TO CRANE
STEEL BLOCK
COPPER COILS (INSIDE BLOCK)
MAGNETIC SCRAPS BEING LIFTED

Fig. 9.39

Uses of the electromagnet :

Electromagnets have different shapes depending on their purpose Fig. 9.39 shows a horse-shoe electromagnet holding a weight suspended from it. The horse-shoe electromagnet possesses more lifting force than a bar electromagnet because it attracts by its two poles simultaneously. Electromagnets are used for lifting heavy masses of iron and steel such as girders, scrap iron, or a cargo of nails, for separating iron and copper scraps for picking out tins and iron from a city's refuse, and in hospitals, for drawing out pieces of iron lodged in the human eye.

Electromagnets are also used when iron ore is to be separated from rocks in iron ore mines (Fig. 9.40).

Tramcars are fitted with a slipper electromagnetic brake. The slipper consists of an iron block carried just above the rail ; the upper part of the block is wound as an electromagnet. When the current is switched on, the block is attracted to the rail and acts as a very efficient brake.

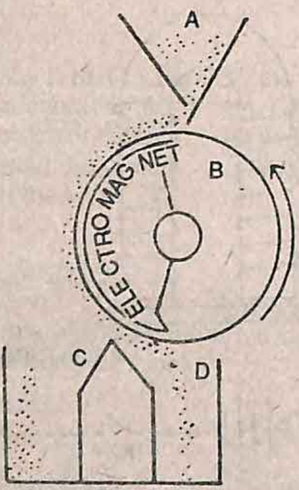


Fig. 9.40

Lamps are made with an electromagnet in the base which clings to iron when the lamp is switched on.

Other most useful applications of electromagnets are :

(*i*) The electric bell (ii) Electric Telegraph (iii) Telephone (iv) Dynamos or generators (v) Electric motor (vi) Microphone, etc.

9.21 FORCE ON A CURRENT CARRYING CONDUCTOR IN A MAGNETIC FIELD (FLEMING'S LEFT HAND RULE)

Magnetism Affects Current :

We have seen that when a magnetic needle is placed near a wire carrying a steady electric current, the magnetic needle experiences forces tending to move its poles in directions perpendicular to the wire. In accordance with the principle of action and reaction, one would expect that there would be equal and opposite forces exerted on the wire carrying the current. For this, let us do the following activity:

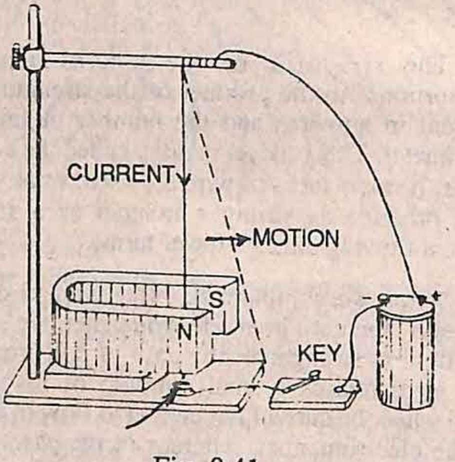


Fig. 9.41

Loosely support a long thick copper wire from a copper wire loop (Fig. 9.41) so that it hangs vertically between the poles of a horse-shoe magnet, with its lower end just dipping into mercury held in a small metal cup. Connect the mercury in the cup and the copper loop through a tapping key to a dry cell. Close the key and observe the action on the conductor.

You will see that the wire is observed to move in a direction at right angles to the magnetic lines of force of the magnetic field between the poles of the horse-shoe magnet. This indicates that a *force acts upon a current-bearing conductor placed in a magnetic field. Now change the direction of the current flow in the conductor and observe the effect in the conductor. This time the copper wire is found to move in the opposite direction.

---

* Magnetic field does not exert a force on the wire. *It exerts a force on a moving charge whether it moves in a face space or in a wire.* Since the charges moving in a wire are confined to the body of the wire, the wire itself experience a force.

Now turn the horse-shoe magnet by 180° keeping the copper wire in-between the poles of the magnet *i.e.*, interchange the positions of North and South poles of the magnet and thereby change the direction of the lines of force of the magnetic field. Now switch on the current in the copper wire and observe the effect on it. You will find it to be deflected in a direction opposite to the previous one (Fig. 9.42).

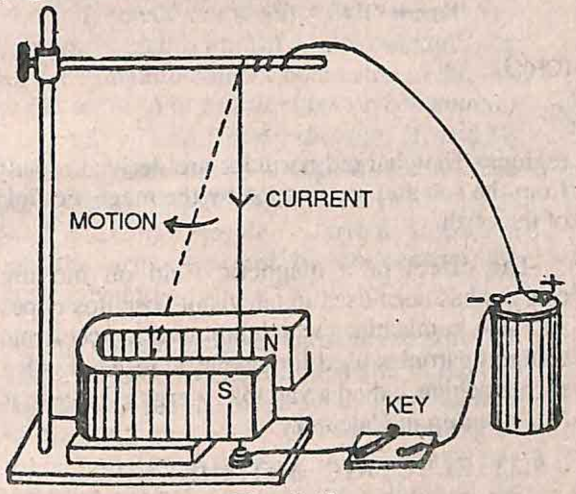


Fig. 9.42

So we conclude that the direction of the mechanical force upon the current-bearing conductor placed in a magnetic field depends upon :

(i) the direction of the flow of current in the conductor ; and

(ii) the direction of the magnetic field.

From experiments it has been found that the direction of this mechanical force is perpendicular to both, the direction of the magnetic field and the direction of the current in the conductor.

The *magnitude* of the mechanical force (F) experienced by the wire carrying current is proportional to the current (I) it carries and also the length (l) of the wire that is in the magnetic field *i.e.*,

$$F \propto I\,l$$

or $$\boxed{F = B.I\,l}$$

where $\vec{B}$ is a constant of proportionally and is known as the *magnetic field*. It is a *vector* quantity.

In the SI units, F is measured in newton, I in ampere and l in metre. Thus $B = \frac{F}{I.l}$ is measured in *newton per ampere-metre*. This unit, newton per ampere-metre, is called *tesla* (T). A smaller unit to measure magnetic field is *gauss* because **tesla** is a fairly big unit.

$$\boxed{1 \text{ gauss} = 10^{-4} \text{ tesla}}$$

Magnetic field of the earth near the surface is about 0·3 gauss.

Fleming's Left – Hand Rule is a convenient rule for helping to remember which way the current-carrying conductor in a magnetic field would move.

The thumb, and first finger and middle finger of the *left* hand are held *mutually at right angles* to each other (Fig. 9.43). Then the direction of

(a) the *Field* is represented by the *first finger*.

(b) the *Current* is represented by the *middle-finger*, and

(c) the *Motion* of the conductor is represented by the *thumb*.

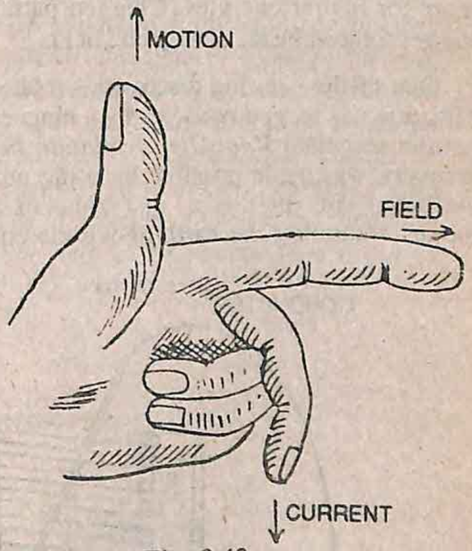


Fig. 9.43

Earlier we have studied that an electric current is just a flow of charges. Thus, moving charges in free space, like currents in a wire, also experience force in a magnetic field. The direction of the force on a moving positive charge is exactly the same as that of a current and is give by Flemings left-hand rule. In the case of a moving *negatively* charged particle the direction of the force is *opposite* to that on similarly moving positive charge. On account of this force, if a moving charged particle enters a

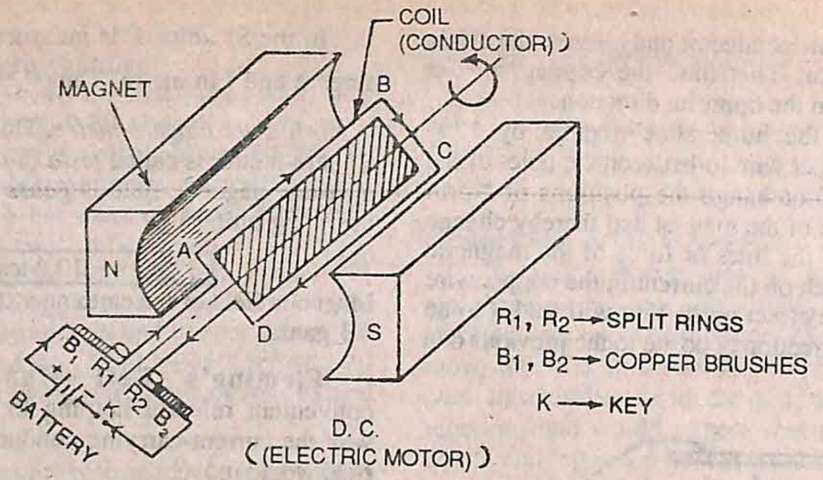


Fig. 9.44

magnetic field which is *perpendicular* to its motion, it experiences force perpendicular to both, its velocity and the field. Hence it is deflected from its straight line path. If the field is uniform and the particles move in a plane normal to it, *then they will move in a circle* ; the radius of the circle being larger for higher energies. Charged particles can thus get *trapped* inside a magnetic field.

One of the exciting discoveries related to the deflection of charged particles by a magnetic field was the so-called *Van Allen radiation belt*. This discovery was made possible by using unmanned satellites. This belt is a vast zone of trapped charges encircling the earth above the equatorial regions. The charged particles are derived mostly from the sun and are trapped by the magnetic field of the earth.

The effect of a magnetic field on moving charges has been used in television, oscillos-copes and also in machines which are used to accelerate charged particles used for scientific research. One such machine, called a variable energy *cyclotron* is being put up in Calcutta.

9.22 ELECTRIC MOTOR

An **electric motor** *is a device which changes electrical energy into mechanical energy.*

It is found that if a conductor carrying current

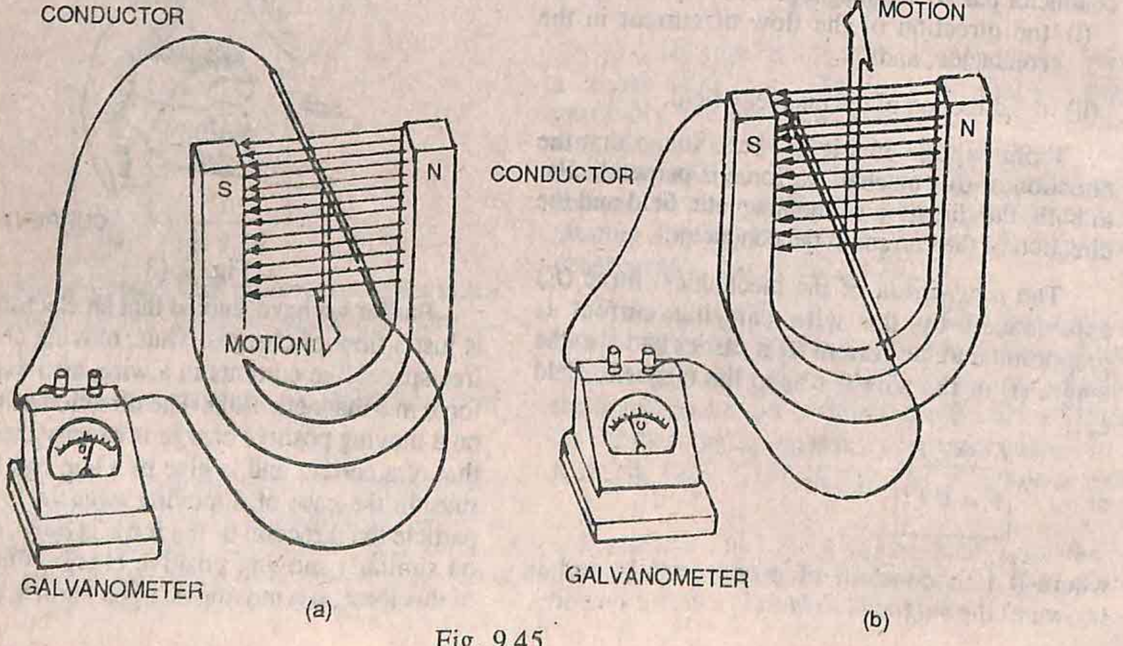


Fig. 9.45

(or a *live* conductor) is placed in a magnetic field, it experiences a force and hence begins to move. This action is known as the *motor effect*. The direction of motion of the conductor is given by Fleming's Left-Hand Rule.

There are different types of electric motors. Motors are made for working on different voltages. Some work only on alternating current (A.C.); some only on direct current (D.C.) and some work on both A.C. and D.C.

The principle of a D.C. motor is shown in (Fig. 9.44). It consists of a coil ABCD wound on a soft iron-core which is known as the *armature*. The ends of the armature coil are connected to the two halves (R_1 and R_2) of a *split rings* or *commutator* made of copper. Two *Copper brushes* B_1 and B_2 lightly press against the split rings R_1 and R_2. The armature coil is placed between the two poles N and S of a *strong magnet*. Current is passed through the armature coil by connecting the brushes to a battery.

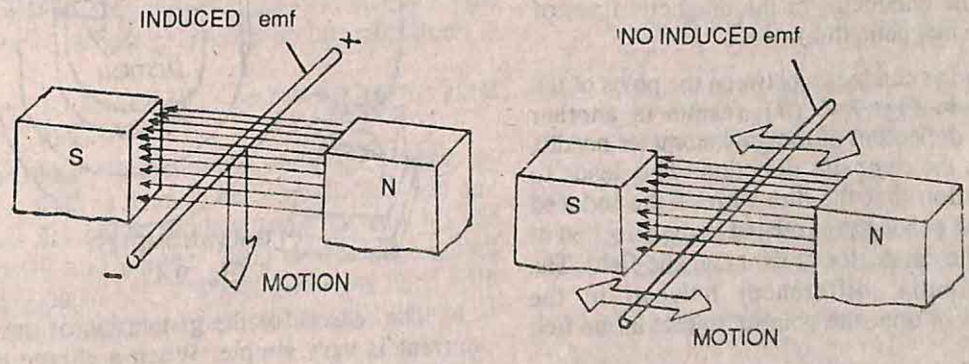
When a current is passed through the armature coil ABCD, a force will act on each arm of the coil as it is placed in the magnetic field. The magnetic field pushes AB down and CD up according to Fleming's Left Hand Rule. This moves the coil anticlockwise. At half rotation, the polarity of the commutator changes since now it is R_2 which contacts the brush B_1 and R_1 contacts B_2. This reversal pushes CD down and AB up. Thus the armature coil begins to rotate and a continuous rotatory motion is obtained. The rotation of the armature coil can be conveyed by means of a belt to any machine.

Applications :

Electric motors are used in industry and in domestic appliances such as lathes, drills, table fans, ceiling fans, washing machines, refrigerators ; mixers ; vacuum cleaners ; blowers ; electric pumps. Theyn are also used in electric lifts, cinema projectors ; electric trains and trams.

9.23 ELECTROMAGNETIC INDUCTION

In 1819 Oersted discovered that an electric current produces a magnetic field in the space around it. Efforts started immediately to produce an electric current with a magnetic field. In 1831 this was finally achieved independently by Micheal Faraday in England and by Joseph Henry in the United States. Faraday proved beyond any doubt that *an electric current can be induced in a closed circuit by varying the magnetic field intensity or the number of magnetic lines of force passing through the circuit. The change of magnetic lines of force can be produced by a* **relative motion** *between the circuit and a magnetic field produced either by a magnet or by another circuit or conductor carrying an electric current. This phenomenon of production of an electric current in a circuit by the help of a magnetic field is called* **electromagnetic induction.**



(A) CHANGE IN FLUX LINKAGE (B) NO CHANGE IN FLUX LINKAGE

Fig. 9.46

The current produced in this way is called **induced current**. In its nature it is not different from other electric currents. The electro-motive force (*e.m.f.*) or potential difference producing such current is known as **induced e.m.f.** (or induced potential difference).

The number of magnetic lines of force (or magnetic flux) through a closed circuit may be changed by one of the following ways :

1. by moving a magnet in the vicinity of the circuit,
2. by changing a current flowing in a circuit lying near the given circuit,
3. by varying the distance of the given circuit from another circuit carrying current,
4. by changing the current in the circuit itself, and
5. by moving the circuit itself in the magnetic field.

We shall examine some of Faraday's experiments to understand their significance. Suppose we connect a sensitive galvanometer in a closed conducting loop as shown in Fig. 9.45. A segment of the conductor is poised in the field flux (magnetic lines of force) of a strong magnet. In Fig. 9.45 (A), as the conductor is moved down between the poles of the magnet, there is a momentary deflection of the galvanometer needle, indicating an induced current. The needle shows no deflection when the conductor is stationary in the magnetic lines of force. This leads to the observation that the induced current is related to the motion of the conductor in the magnetic lines of force (or the magnetic flux).

Raising the conductor between the poles of the magnet, as in Fig. 9.45 (*B*), results in another momentary deflection of the galvanometer needle, this time in the *opposite* direction. This leads to the observation that the direction of the induced current in the conductor is related to the direction of motion of the conductor in the magnetic field. The *e.m.f.* (potential difference) induced in the conductor is of opposite polarity to that in the first experiment.

Faraday found that he could induce an *e.m.f.* in a conductor either by moving the conductor through a stationary magnetic field or by moving the magnetic field near a stationary conductor. He observed that the direction of the induced current in the conducting loop is reversed with a change in either the direction of motion or the direction of the magnetic field.

Support the conducting loop of Fig. 9.45 in a fixed position and lift the magnet. It results in a deflection similar to that of Fig. 9.45 (*A*). When the magnet is lowered the galvanometer needle is momentarily deflected as in Fig 9.45 (*B*). The relative motion between the conductor and the magnetic field is the same whether the conductor is raised through the stationary magnetic field or the magnetic field is lowered past the stationary conductor.

So far, we have considered the relative motion of the conductor to be essentially *perpendicular* to the magnetic lines of force (magnetic flux). If the conductor is moved in the magnetic field *parallel* with the magnetic lines of force, no *e.m.f.* is induced and no deflection is observed in the galvanometer. (See Fig. 9.46).

Suppose the conductor is looped so that several turns are poised in the magnetic field as in Fig. 9.47. When the coil is moved down between the poles of the magnet as before, there is a greater deflection in the galvanometer. By increasing the rate of motion of the coil across the magnetic lines of force, greater deflections are produced.

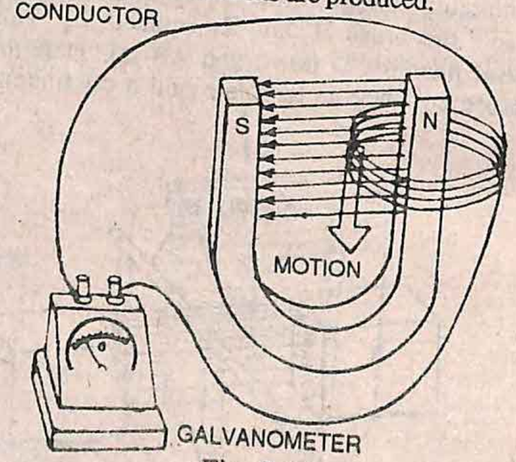


Fig. 9.47

The reason for the generation of the induced current is very simple. When a charge moves at right angles to a magnetic field, the field exerts a force on the charge which is perpendicular to this motion as well as to the field. Now, when we move the conductor across a magnetic field, we are really moving the electrons and other particles in the conductor across the magnetic field. The magnetic field will exert a force on these charges, and some of these electrons are free to move in the direction of the force. This results in the induced current, if the conductor is part of a complete circuit. If the conductor is not part of a complete circuit, excess electrons pile up at one end of the conductor, making it negative. The other end will have a deficiency of electrons and be positive.

The direction of the induced current is given by **Fleming's right-hand rule** (Fig. 9.48) which is stated below :

Stretch the thumb, the fore-finger and the central finger of the right-hand mutually perpendicular to one another. If the thumb represents the direction of motion of the conductor, the fore-finger represents the direction of the magnetic field, then the central finger points in the direction in which current is induced in the circuit.

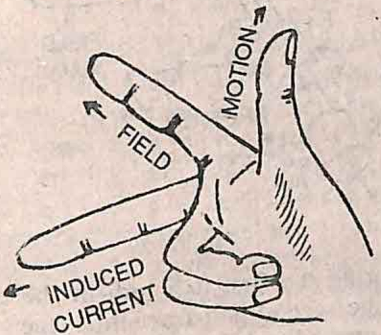


Fig. 9.48

Modern technology is largely dependent on the production and distribution of inexpensive electric power. These accomplishments were made feasible by the discoveries of Faraday which led to the invention of electric generators and transformers.

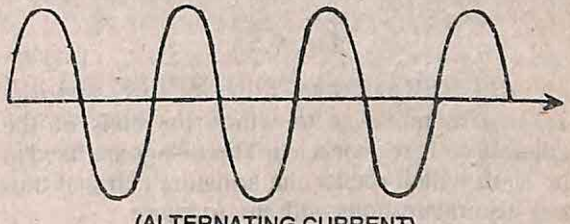
9.24 ELECTRIC GENERATOR (OR DYNAMO)

The induced current observed in the experiment in Art. 9.23 is usually very small. But one can construct devices to produce large currents for use in industry and homes. Such devices are called *electric generators.* A small generator used with bicycle and other vehicles is popularly known as *dynamo.*

An electric generator (or dynamo) is, thus, a machine used for generating electric current by mechanical means, or a machine in which mechanical energy is changed into electrical energy.

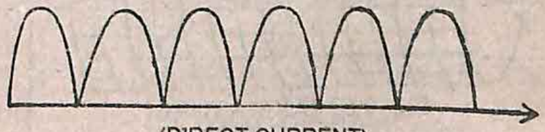
It works on the principle of electro-magnetic induction *i.e.*, whenever the number of magnetic lines of force passing through a conductor (a wire or a rod) is varied, an *emf* (or current) is induced in it. The strength of the *emf* (or current) produced is directly proportional to the strength of the magnetic field and the speed with which the conductor moves. The direction of the induced current is given by Fleming's right-hand rule (Art 9.23).

When the electric current produced by a dynamo or an electric generator *changes its direction of flow continuously and periodically in a circuit several times in a second*, the current is known as an *alternating current* (A.C.) and the machine that produces it is known as an *alternating current generator* (*A.C. Generator*) or A.C. Dynamo. An alternating current is shown graphically as in Fig. 9.49. When the electric current produced always flows *in and the same direction and has a constant strength*, it is known as *direct current* (*D.C.*) (Fig 9.50) and the machine that produces it is known as *direct current generator* (D.C. Generator) or D.C. Dynamo.



(ALTERNATING CURRENT)

Fig. 9.49



(DIRECT CURRENT)

Fig. 9.50

A simple electric generator is shown in Fig. 9.51. It consists of four main parts :

(i) **Armature**. Armature *ABCD* consists of a large number of loops or coils of insulated wire wound on a soft iron drum, (Fig. 9.52) or ring. It revolves round an axle between the two poles of a strong magnet and this cuts the magnetic lines of force running from north pole to the south pole.

This drum or ring of soft iron serves two purposes : (*a*) it serves to support the coils and (*b*) increases the magnetic field by substituting iron for air core for magnetic lines of force.

(*ii*) **Field Magnets**. The magnetic field is produced by a permanent magnet in the case of very small low power dynamos and by electromagnet in the case of big dynamos. In the latter case the electromagnet (*N* and *S*) is excited by the current generated by a small direct current generator mounted on the same axle and driven by the same power which keeps the dynamo armature rotating.

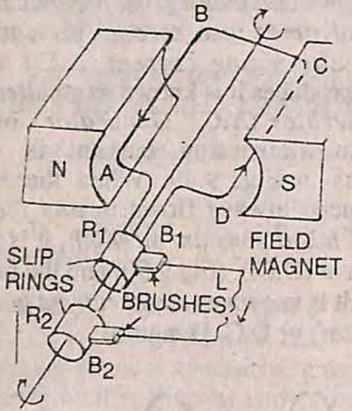


Fig. 9.51

(*iii*) **Slip Rings**. Slip rings (R_1 and R_2) are two metal rings to which the ends of the armature coil are connected. These rings are fixed to the shaft which rotates the armature coil and thus they also rotate along with the armature.

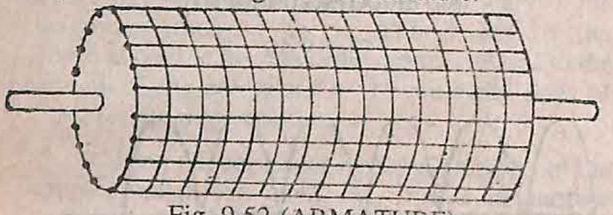


Fig. 9.52 (ARMATURE)

(*iv*) **Brushes**. These are two flexible metal plates or carbon rods (B_1 and B_2) which are fixed and constantly touch the revolving rings. It is with the help of these brushes that the current is passed on from the armature and rings to the main wires which supply the current to the lamps (*L*) in the streets and houses.

Working. The principle of working of an electric generator will be clear from Fig. 9.51.

Suppose the armature coil *ABCD* rotates in the *anticlockwise* direction. As it rotates, the magnetic flux linked with it changes and the current is induced in the coil, the direction of which is given by Fleming's Right Hand Rule. Considering the armature to be in the vertical position and as it rotates anticlockwise, the wires *AB* move downwards and *DC* move upwards, the direction of the induced *emf* is from *B* to *A* and *D* to *C* *i.e.* in the coil it flows along *DCBA*., (Fig. 9.51). In the external circuit the current flows along B_1LB_2. This direction of current remains the same during the first half turn of the armature. During the second half revolution, the wires *AB* move upward while the wires *CD* move downwards. The current flows in the direction *ABCD* in the armature coil, Fig.. 9.53. *i.e.*, the direction of induced current in the coil is reversed. In the external circuit the current flows along B_2LB_1. Therefore, the direction of the induced *emf* and the current changes in the external circuit also after every half a revolution. Hence the current thus produced is **alternating** in nature (Fig. 9.54).

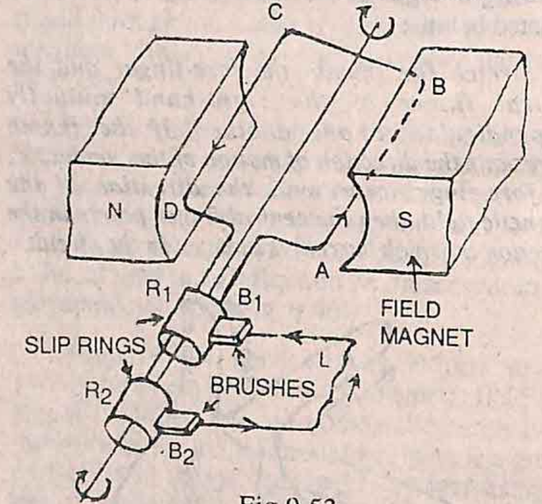


Fig.9.53

However, the magnitude of the induced *emf* and hence that of the induced current is not constant. When the coil is in the vertical position $\theta = 0^0$, maximum number of lines of force is passing through it but the number of lines of force cut is zero. Hence induced *emf* is zero. As the coil rotates, the rate of cutting of magnetic lines of force goes on increasing and it is maximum when the coil is in the horizontal position, $\theta = 90^0$. Thus the magnitude of the induced *emf* is maximum. When the coil rotates further the rate of variation in the number of magnetic lines of force cut by the coil again decreases and induced *emf* falls to zero at the position when $\theta = 180^0$. The coil in this case is once more vertical to the magnetic lines of force.

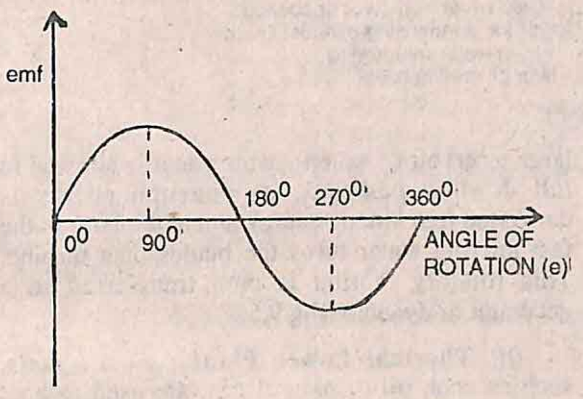


Fig.9.54

When the coil rotates further, the induced *emf* and hence induced current starts in the opposite direction and rises to the maximum value at $\theta = 270^0$ and again falls to zero at $\theta = 360^0$, the direction remaining the same. These changes are shown in Fig. 9.54 graphically. Such a current which changes direction after equal intervals of time is called an alternating current and the device shown in Fig. 9.51 is called an A.C. generator or A.C. dynamo. Most power stations constructed these days produce A.C. in India ; the A.C. changes direction after every 1/100 second, *i.e.*, the frequency of A.C. is 50 Hz.

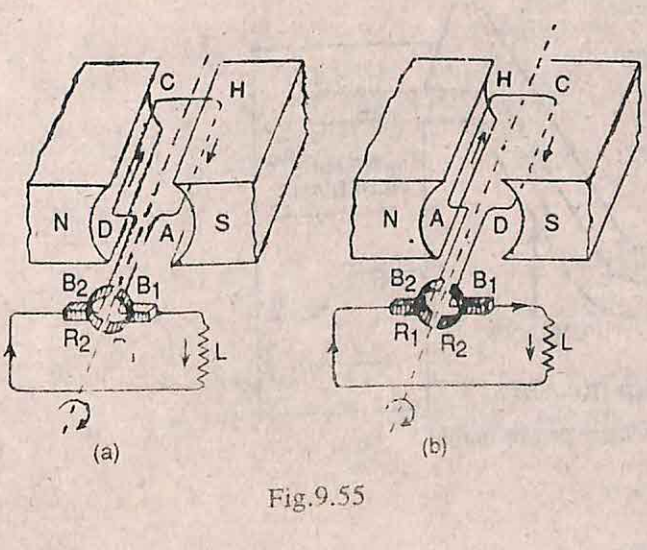


Fig.9.55

A very important advantage of A.C. is that it can be transmitted over long distances without much energy loss. A.C. dynamos are used in industry and electric power plants.

D.C. Dynamo : A *D.C* or direct-current generator can be constructed with a slight modification of the above A.C. generator. We use the same field magnet and armature coil, but instead of slip rings, we use *split rings* (or a *commutator*) R_1 and R_2 which are halves of the same ring as shown in Fig. 9.55 (a). The ends of armature coil are connected to these rings and the rings rotate with the armature and change the contact with the brushes B_1 and B_2.

The working of a D.C. dynamo is similar to that of an A.C. one. Let the coil be rotated in the *clockwise direction*. The current produced in the armature is A.C. but the commutator changes it into D.C. in the outer circuit. In the first half cycle, [Fig. 9.55 (a)] the current flows along $B_1LB_2R_2DCHAR_1B_1$. The current in the external circuit flows along B_1LB_2. In the second half cycle, Fig. 9.55 (b), current in the armature is reversed and flows along R_1AHCDR_2 and as the ring R_1 comes into contact with the brush B_2 and the ring R_2 comes into contact with the brush B_1. The current in the circuit now flows along $B_1LB_2R_1AHCDR_2B_1$. The current in the external circuit again flows from the brush B_1 to B_2. *Thus the current in the external circuit always flows in the same direction.*

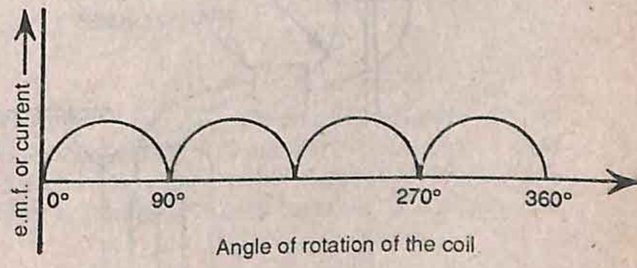


Fig. 9.56

The current produced in the outer circuit is graphically represented in Fig. 9.56 as the coil is rotated from the vertical position perpendicular to the magnetic lines of force. The current generated by such a simple D.C. dynamo is *unidirectional but its value varies considerably and even falls to zero twice during each rotation of the coil.*

D.C. dynamos are used in bicycles and cars.

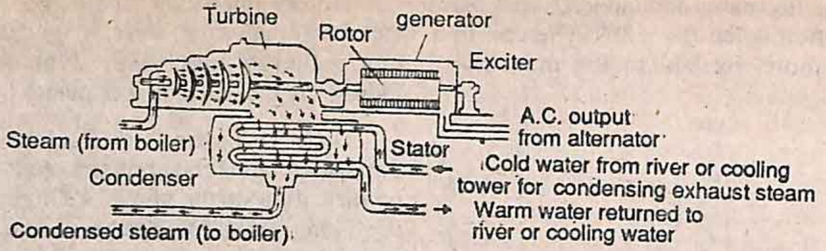

Turbine
Rotor
generator
Exciter
A.C. output from alternator
Steam (from boiler)
Stator
Condenser
Cold water from river or cooling tower for condensing exhaust steam
Warm water returned to river or cooling water
Condensed steam (to boiler)

Fig. 9.57

9.25 ELECTRIC POWER PLANTS

The principle on which a dynamo or a generator works (*i.e.* the generation of electricity by rotating a coil in a magnetic field) is used to produce large amounts of electriciy in power plants and stations. The power produced may be a few kilowatts in diesel generator sets (gensets) or as high as a few hundred megawatts (mega = million = 10^6) in atomic power plants or hydroelectric stations.

The coil is fixed on a common shaft with a turbine. A turbine has a rotor with blades or vanes and is driven by the pressure of moving water, steam or air (Fig. 9.57). When the turbine rotates, the coil rotates with it and generates electricity by electromagnetic induction. At present four different types of power plants are in use to produce most commercial electric power.

(i) **Hydroelectric Power Plant** : In hydroelectric power plants, a dam is used to create a large reservoir of water. As the water is allowed to fall down a *penstock*, its potential energy is converted into kinetic energy and at the bottom the fast moving water turns the blades of a turbine. This rotatory motion is then transferred to a generator or dynamo (Fig 9.58).

(ii) **Thermal Power Plant** : *Fossil fuels*, such as coal, oil or natural gas, are used to heat water, producing high pressure steam in a boiler. The steam then flows past the blades of a turbine into a low pressure area, and the rotation of the turbine is transferred to a generator which produces electricity. Thus the chemical energy of the fossil fuel (coil, oil, gas) is converted into thermal energy of steam which is converted into mechanical energy of the blades of the turbine. Finally the dynamo or generator converts this mechanical energy of the turbine into the electrical energy.

(iii) **Diesel Generator** : In internal combustion engines, such as diesels fuel (diesel

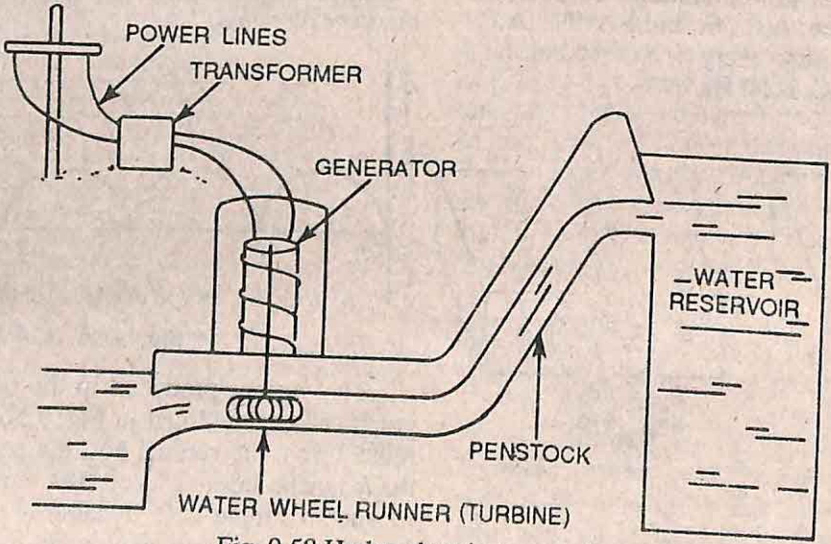


Fig. 9.58 Hydro-electric power plant

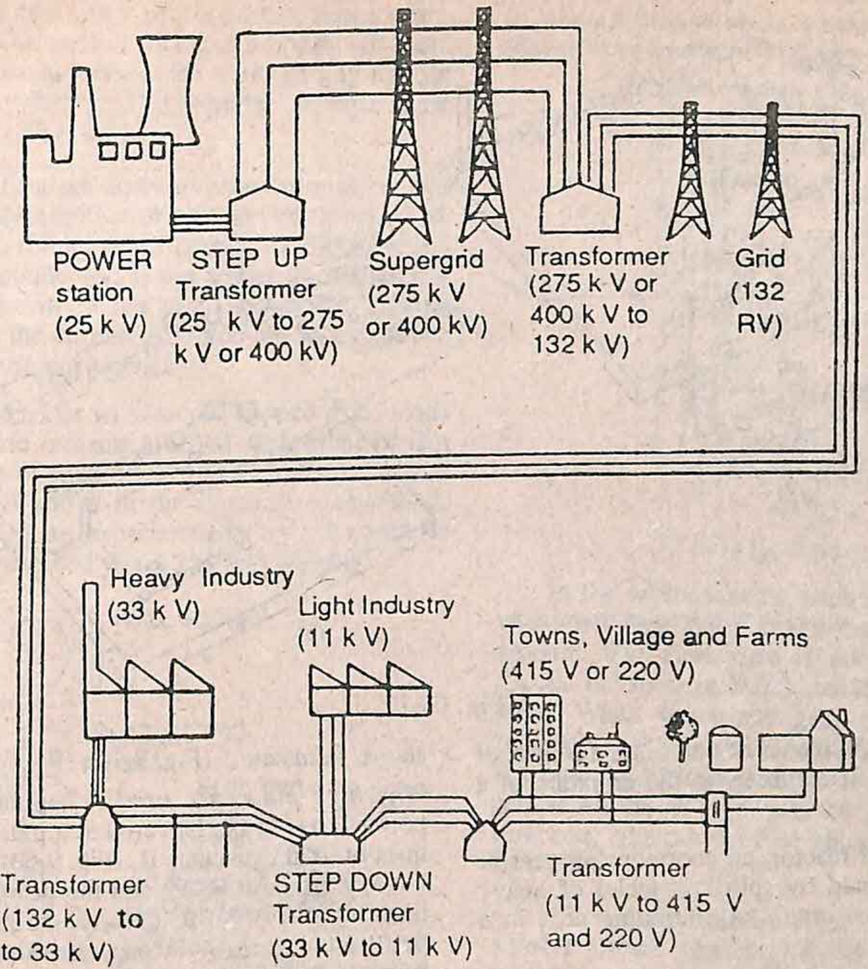

POWER station (25 k V)
STEP UP Transformer (25 k V to 275 k V or 400 kV)
Supergrid (275 k V or 400 kV)
Transformer (275 k V or 400 k V to 132 k V)
Grid (132 RV)
Heavy Industry (33 k V)
Light Industry (11 k V)
Towns, Village and Farms (415 V or 220 V)
Transformer (132 k V to to 33 k V)
STEP DOWN Transformer (33 k V to 11 k V)
Transformer (11 k V to 415 V and 220 V)

Fig. 9.59

oil) is burnt and the rotary output is used to turn the rotor of a generator. This type of power plant is used at isolated locations (shops or buildings) or in regions that have vast quantities of natural gas or fuel oil.

(iv) **Atomic Power Plant or A Nuclear Reactor :** A *nuclear reactor* can be used to generate a considerable amount of heat, which super heats steam to high pressure. The steam then

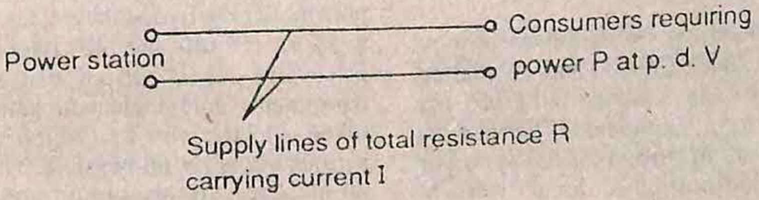

Power station
Consumers requiring power P at p. d. V
Supply lines of total resistance R carrying current I

Fig. 9.60

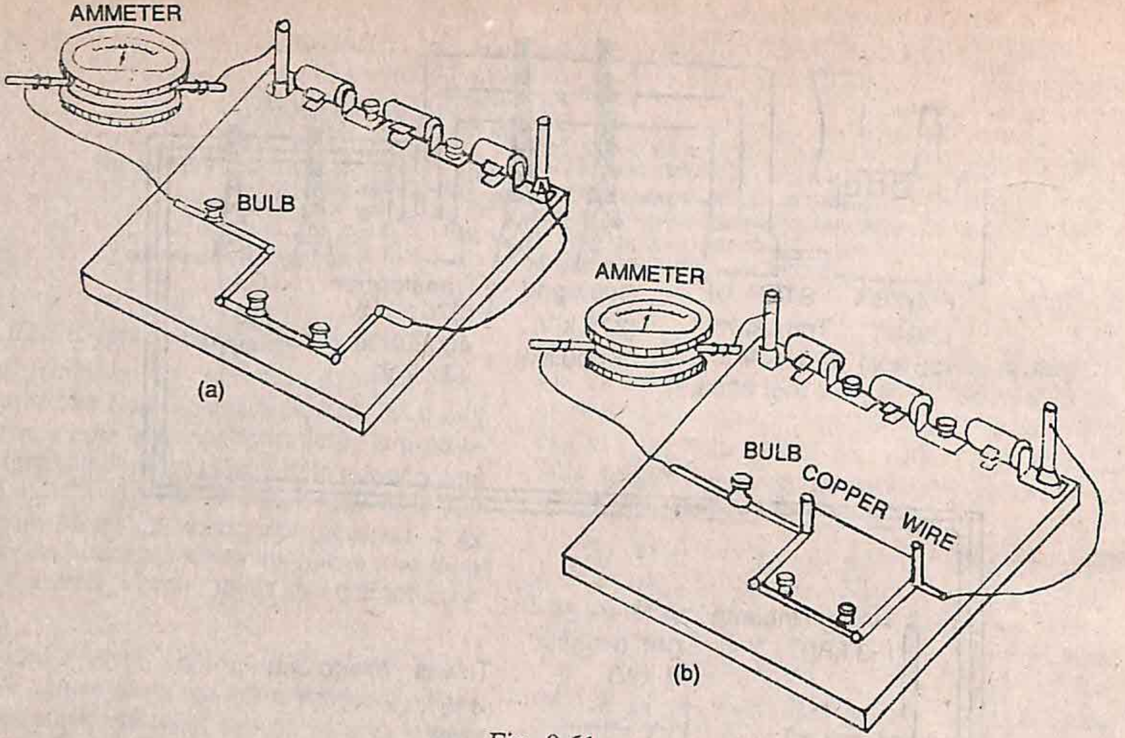


Fig. 9.61

passes through the blades of a turbine, the shaft of which is connected directly to the armature of a generator.

In a nuclear reactor, an enormous amount of energy is obtained by splitting nuclei of heavy elements such as uranium, plutonium etc., in a nuclear fission reacion.

Wind generators are used experimentally.

The electrical power produced in these power plants is usually alternating current (A.C.) and the voltage may be as high as 25 *kV*.

Once the electrical energy has been produced, it is normally transmitted from one place to another in a conductor called a **transmission (power) line.**

Long Distance Transmission of Electrical Power :

In the largest modern power stations electricity is generated at about 25 kV (50 Hz) and stepped up in a transformer to 275 kV or 400 kV for transmission over long distances. The p.d. is subsequently reduced in sub-stations by other transformers for distribution to local users at suitable p.d.s.; 33 kV for heavy industry, 11 kV for light industry and 220 V for homes, schools, shops, farms etc.,. (Fig. 9.59).

Why high p.d.s. are used : Suppose electrical power P has to be delivered at a p.d. V by supply lines of total resistance R, (Fig. 9.60). The current I = P/V (since P = IV) and the power loss in the lines = $I^2R = (P/V)^2R$. Clearly, the greater V, the smaller is the loss—in fact, doubling V quarters the loss. Electrical power is thus transmitted more economically at high p.ds. but on the other create *insulation* problems and raise *installation* costs.

9.26 ELECTRIC FUSE

Electricity can be very *dangerous*. It must therefore be treated with great respect and only by those of us who know how to use it and take every safety protection.

The dangers are real. (1) A short circuit can cause a fire, an explosion or shock damage to a person. (2) Faulty insulation can be responsible for a short circuit and all its consequences. (3) Excessive large current can seriously damage equipment. Unless adequate safety precautions are taken, electric shocks (which could be fatal) or serious burns are all possible. The heating effect of an electric current is rapid and could be quickly responsible for much damage.

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* For further knowledge only

A wire gets hotter as the current flowing in it increases. The electric wiring in a house will stand a certain current without the wires getting too hot to cause any damage. But consider the experiment illustrated in Fig. 9.61.

In the first circuit board, the three lamps will glow equally bright with normal brightness. What will happen if a length of copper wire (copper is a very good conductor) is put across the connecting leads as shown in the second diagram ? What happens to the current ? (If you are in any doubt, try the experiment yourself).

Now consider what would happen if the leads to an electric radiator touched each other or if a short length of copper wire accidentally fell across the points *A* and *B* in the illustration Fig. 9.62. (This is NOT an experiment to try ; it could be *very dangerous* and you might get a shock.)

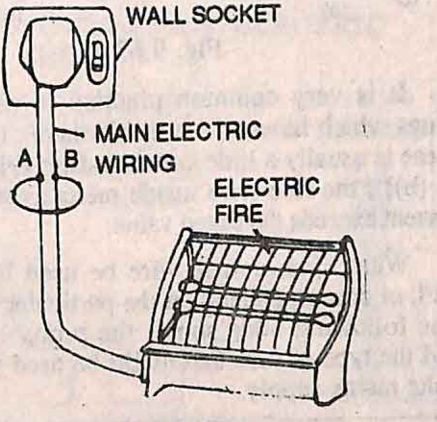


Fig. 9.62

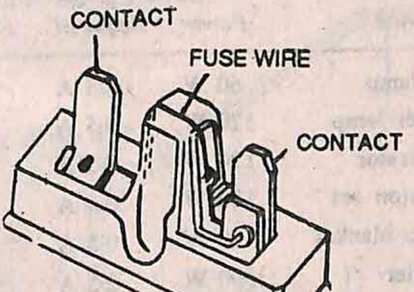


Fig. 9.63

The current would clearly be large indeed, and the mains wire might get very hot and cause a fire unless there was some automatic way of switching off the current. **A small length of wire with a low melting point meets this need.** This **is called a fuse wire. It is made up of tin or some alloy (tin and lead)--(tin 63% + lead 37%).**

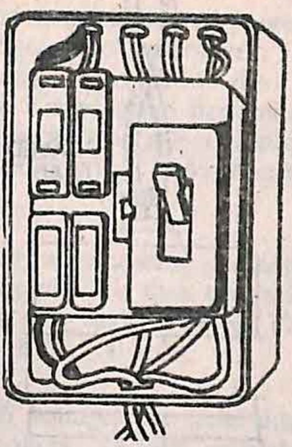


Fig. 9.64

In the wiring circuit, such a fuse is included which will burn out if the current exceeds a stated amount. The fuse wire is normally fixed in a special holder (Fig. 9.63) inside a fuse box (Fig. 9.64). When the current gets too great, the fuse burns out and the main electric wiring is protected. It would be difficult to repair the wire in the wall of a room, but it is an easy business to go to the fuse box, take out the fuse holder and replace the fuse wire.

When the two leads to an electric fire or to another electric appliance touch or are accidently joined in some way as illustrated with the electric fire above, we call it a '*short circuit*' or we say the circuit is '*shorted*'.

It is important to remember that there is always a reason why a fuse wire burns out. It is not good just replacing a fuse wire, as the new fuse wire will burn out again. It may be caused by a family appliance, in which case the appliance, an electric fire, an electric iron or whatever it is, must be disconnected first before repairing the fuse.

Another common cause for a fuse blowing is overloading the circuit. What would happen when the current is switched on if an electric kettle, an electric toaster and an electric fire were all plugged into a light socket using two or three way adaptors ?

It is always wrong to connect electric fires, toasters or kettles, which need quite a lot of current, to the electric light circuit, at the same time.

A common fault is *frayed* leads (Fig. 9.65) or

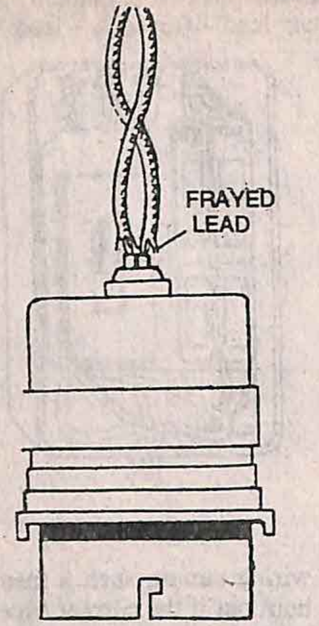


Fig. 9.65

old leads trailing around a room. It is not satisfactory to rely on two lengths of flex tied up

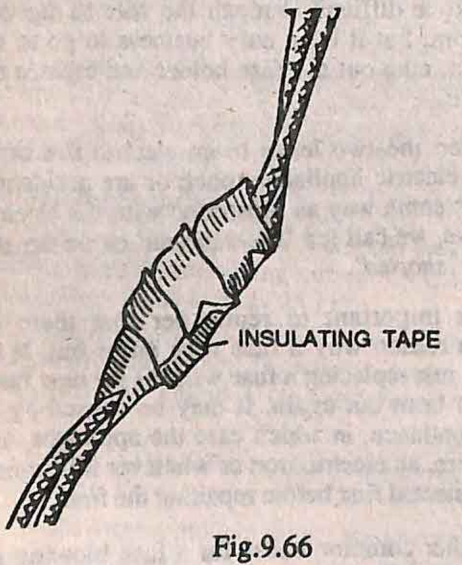
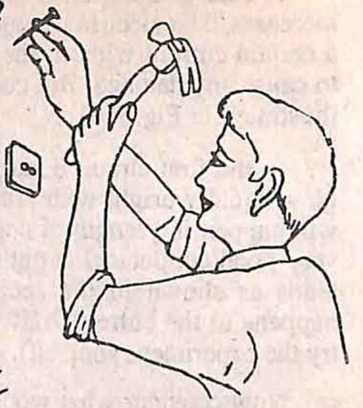
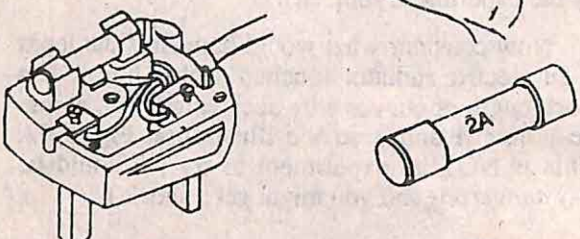


Fig.9.66

together with insulating tape (Fig. 9.66). Such a connection is always a possible source of trouble. Why is it unwise to tack long lengths of flex around the walls of a room ?

What might happen in the picture (Fig. 9.67) illustrated below ? What other causes of fuse-blowing can you think of ? What might happen if one of the leads to an appliance is not securely fixed inside the plug ?





(a) (b)

Fig. 9.67

It is very common practice to use electric plugs which have a fuse inside them. The fuse in these is usually a little cartridge fuse [Fig. 9.67 (a) & (b)] ; the fine wire inside melts as soon as the current exceeds the stated value.

What kind of fuse wire be used in the plug will, of course, depend on the particular appliance. The following table shows the probable currents and the type of fuse that might be used with a 220 volts mains supply.

Appliance	*Power*	*Current Required*	*Fuse Needed For Safety*
Table lamp	60 W	0·25 A	2 A
Stronger lamp	120 W	0·5 A	2 A
Refrigerator	120 W	0·5 A	2 A
Television set	120 W	0·5 A	2 A
Electric blanket	120 W	0·5 A	2 A
Hair drier	600 W	2·5 A	5 A
Electric iron	720 W	3·0 A	5 A
Small electric fire	720 W	3·1 A	5 A
Electric kettle	2000 W	8·3 A	10 to 13 A
Electric fire	2000 W	8·3 A	10 to 13 A
Emmersion heater	3000 W	12·5 A	13 A

In some equipment, instead of a fuse, a *cut out device* is incorporated. This uses the magnetic effect of a current. The current flows through a small coil. When it becomes, too large, the magnetic effect due to this current operates a trip switch, which cuts out the current itself.

What is the advantage of this kind of cut-out over an ordinary fuse ?

While replacing a fuse wire, switch off the supply. Take out the fuse carrier from the fuse unit. Loosen the screws of the fuse carrier and remove the melted wire. Take the new fuse wire of the proper size and thread this wire through the small channel or tube in the carrier. Do not pass the wire through any other easier way between the terminal. Tighten the screws in the terminals of the carrier and replace on the porcelain base of the fuse unit. Switch on the supply. Care must be taken that you *insulate* yourself on a dry wooden-board.

9.27 HOUSE-HOLD ELECTRIC CIRCUITS

You have learnt about the generation of electric power and also about how electricity is transmitted around the country.

Electricity is generated at power stations at many places throughout the country. The necessary energy may come from fuel in the form of coal, gas, or oil. or it may come from nuclear energy within the atom (nuclear power station), or it may come from falling water (a hydro-electric power station).

The power station usually produces electricity at 11,000 volts and it is then transmitted around the country at very high voltages. The National Grid operates at 122,000 volts.

Such high voltages are quite unsuitable for domestic purposes. Various institutions, using transformers, bring the voltage down to 220 volts, at which it will reach you home (Fig. 9.68).

In Art 2-9.26 we discussed the importance of fuses in electric circuits in order to safe-guard

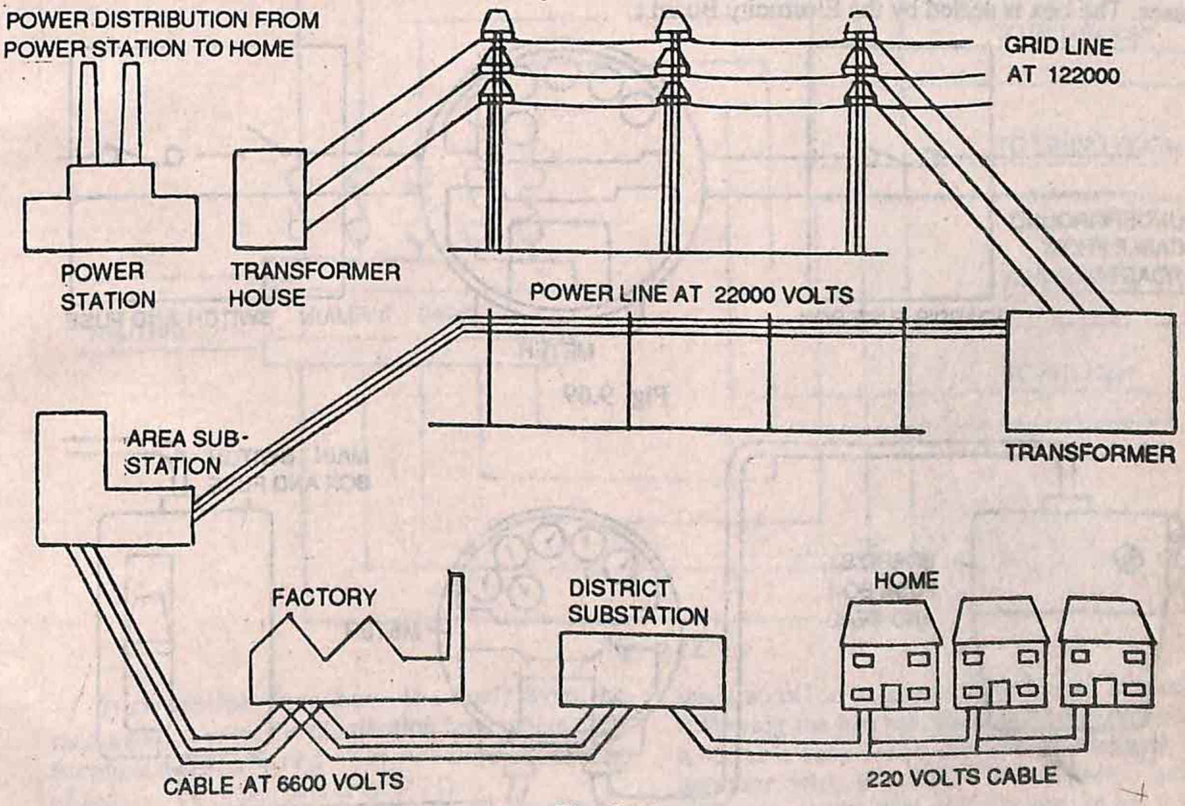


Fig. 9.68

electrical appliances and avoid the danger of fire. Fuses, therefore, play an important part in the electrical wiring system in a house.

In domestic wiring, it is important that the third pin at each socket be connected to earth. For this reason three-cored cable is used ; the *LIVE* wire bringing the electric current is usually coloured *red*, the return wire (often called the NEUTRAL wire) is *black* and the EARTH wire *green*. In order to avoid too much complication in the drawings below showing the wiring in a house, the earth wire has been committed but, of course it is an essential part of the installation.

The Electricity Board's installations. The main cable will pass your house, probably under the road or the pavement outside. A short length of cable joined to the main cable will bring the electricity to your house. This will usually be underground and the cable will enter in the basement or ground floor (Fig. 9.69).

The cable will go into the Electricity Board's main *fuse box* (fig. 9.70). This fuse box usually has a 60-A fuse inside, through which the live lead passes. The box is sealed by the Electricity Board ; it is the Board's property and cannot be opened by you without breaking the seal. If something went seriously wrong with your electric wiring, the Board's fuse would blow and this would protect the rest of their installations and insure that the supply to neighbouring houses did not fail as well. If their fuse blows, the Board's electrician has to come and repair it.

The leads then pass through the meter, which records the electrical energy used. They then go to the main switch. When switched off, none of the lights or appliances in the house will work at all and there can be no possible danger. It is often recommended that, when a house is to be left empty for a long period, the main switch should be turned off.

After the main switch, the electricity has to be distributed around the house. What are the requirements going to be ? There must be fuses. There must be leads going to all parts of the house. There are two ways in which this is commonly done, and both are described blow.

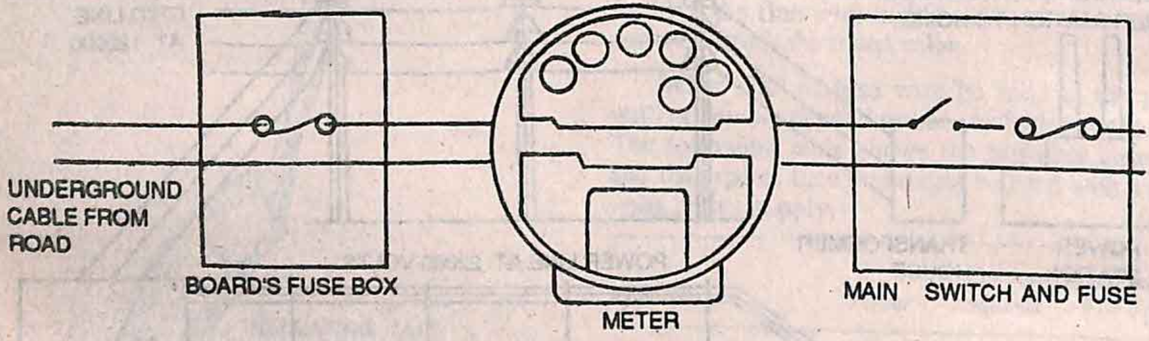


Fig. 9.69

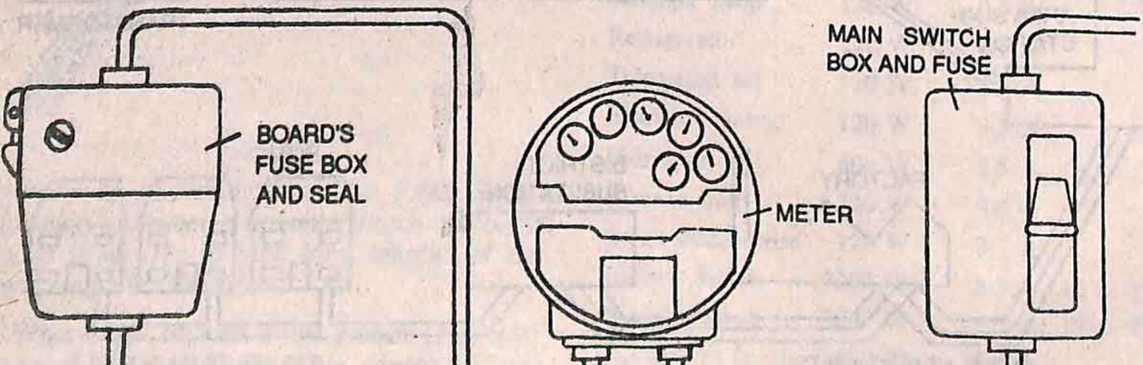


Fig. 9.70

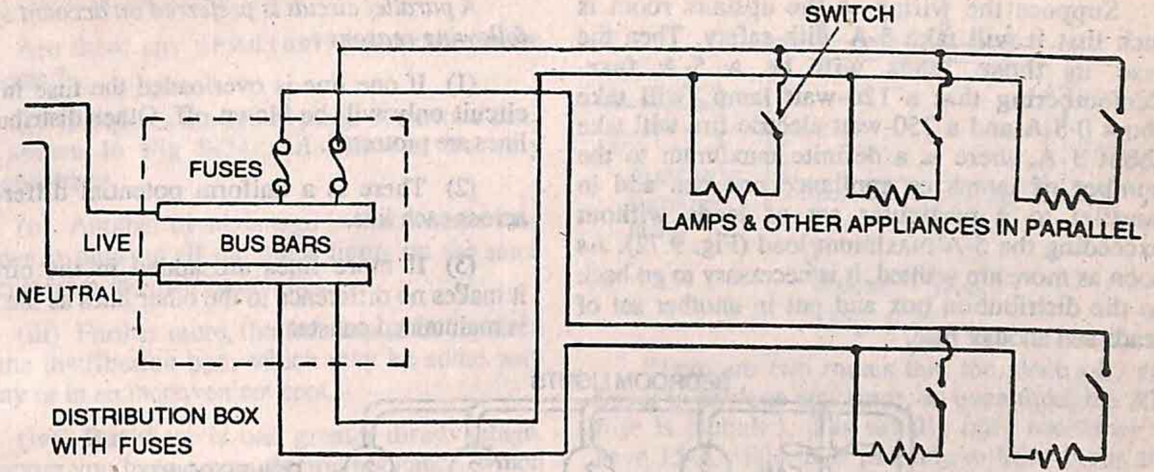


Fig. 9.71

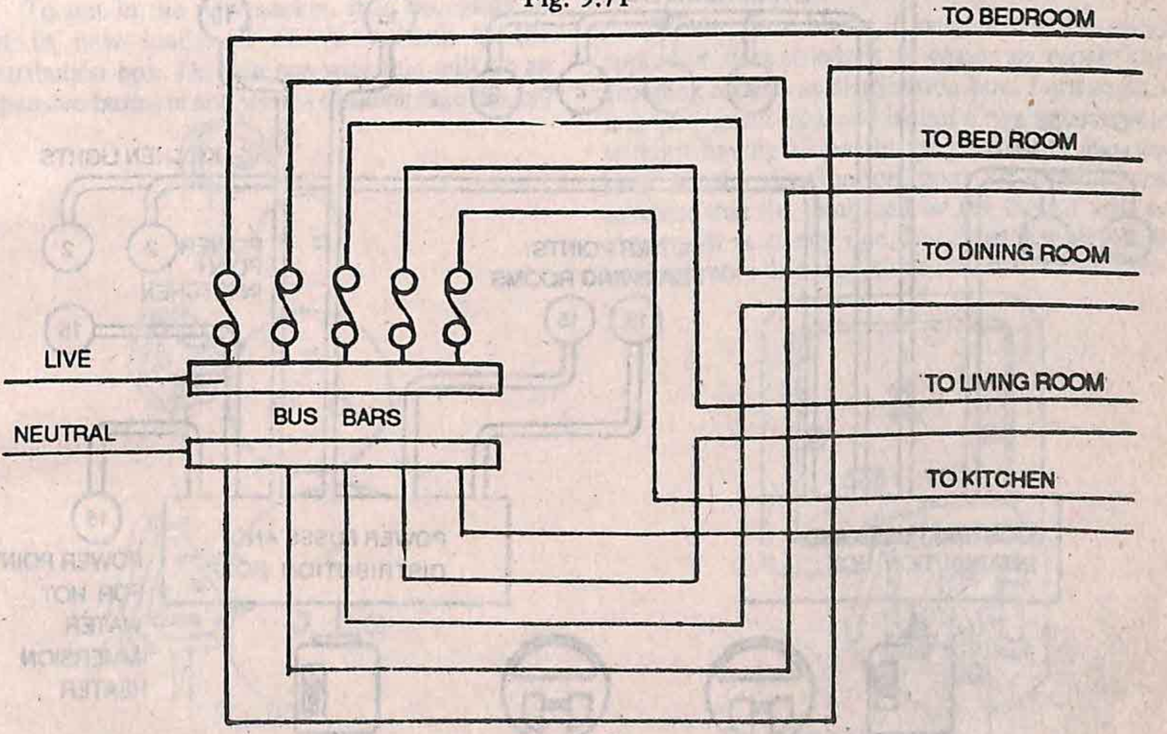


Fig. 9.72

Distribution fuse box. The leads from the mains switch enter the distribution box, where each is connected to a *bus bar*. The two bus bars consist of two thick copper bars (Fig. 9.71).

From the bus bars in the distribution box, leads go off to all parts of the house. Immediately following the bus bar, the *live* lead passes through a suitable fuse. Then the live and neutral leads, together with the third *'earth' wire*, provide electricity in one part of the house. In the diagram only two sets of leads are shown leaving the distribution box, one might be providing lighting up stair, the other lighting in the downstairs rooms.

Suppose the wiring to the upstairs room is such that it will take 5-A with safety. Then the fuse in those leads will be a 5-A fuse. Remembering that a 120-watt lamp will take about 0·5 A and a 750-watt electric fire will take about 3 A, there is a definite maximum to the number of lamps or appliance one can add in parallel to a particular set of leads without exceeding the 5-A maximum load (Fig. 9.72). As soon as more are wanted, it is necessary to go back to the distribution box and put in another set of leads and another fuse.

It should be noted that all distribution circuits have the same potential difference, usually 220 volts, as they are connected in parallel.

A parallel circuit is preferred on account of the following reasons :

(1) If one line is overloaded the fuse in this circuit only will be blown off. Other distribution lines are protected.

(2) There is a uniform potential difference across each line.

(3) If more lines are added in the circuit, it makes no difference to the other lines as the P.D. is maintained constant.

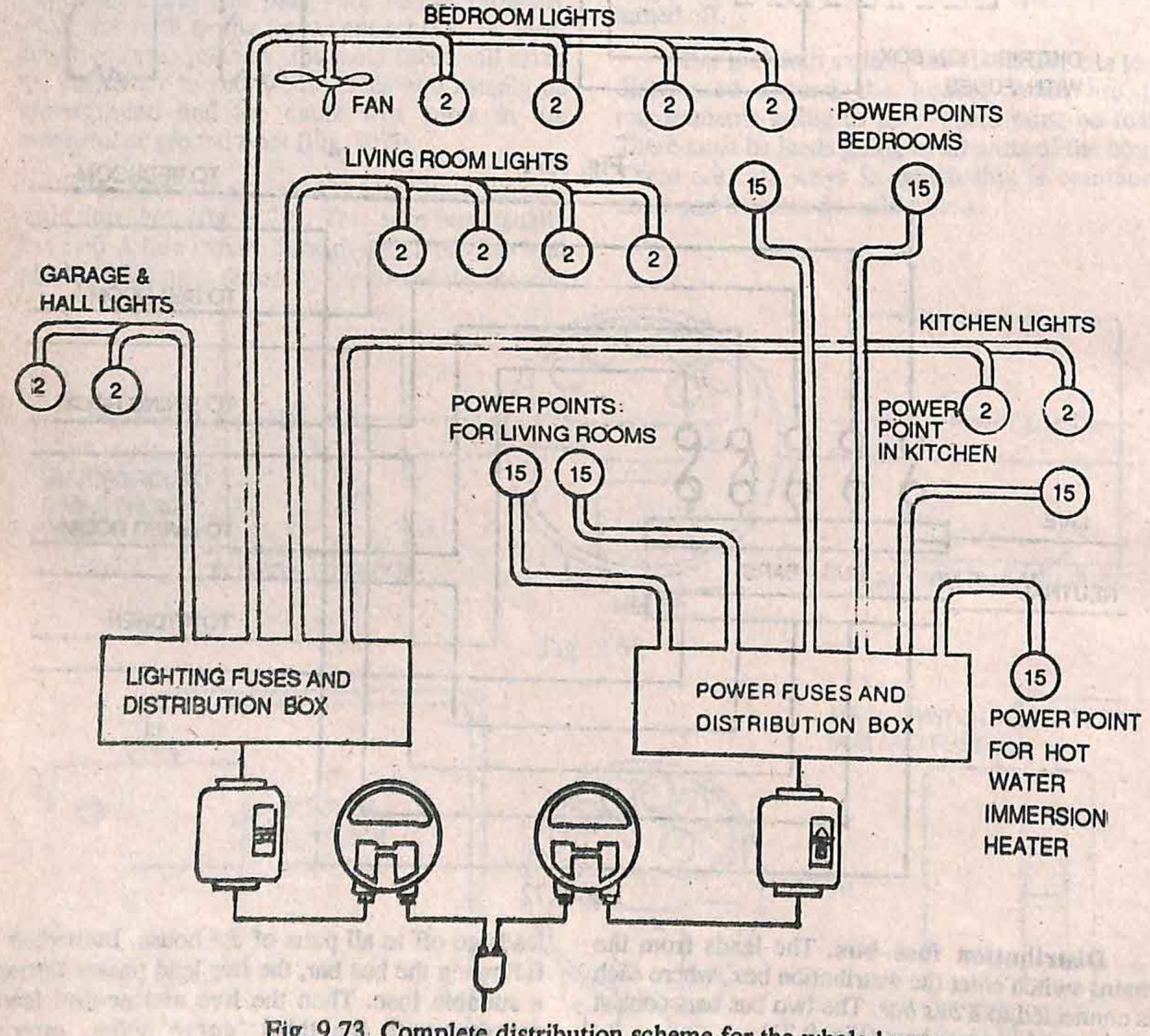

BEDROOM LIGHTS
FAN
2
2
2
2
POWER POINTS BEDROOMS
15
15
LIVING ROOM LIGHTS
2
2
2
2
GARAGE & HALL LIGHTS
2
2
KITCHEN LIGHTS
POWER POINTS FOR LIVING ROOMS
15
15
POWER POINT IN KITCHEN
2
2
15
LIGHTING FUSES AND DISTRIBUTION BOX
POWER FUSES AND DISTRIBUTION BOX
15
POWER POINT FOR HOT WATER IMMERSION HEATER

Fig. 9.73 Complete distribution scheme for the whole house

The complete distribution scheme for the whole of house might be something like this. The figures in the circles give the maximum current that might be used (Fig 9.73).

Are there any **disadvantages** in the above scheme ?

(i) It requires the use of plugs of various sizes as shown in Fig 9.74 and this can be very inconvenient.

(ii) Another disadvantage is that when a fuse blows, it puts out all the other lights on the same circuit from the distribution box.

(iii) Further more, the fuse has to be repaired at the distribution box, which may be some way away or in an inconvenient spot.

(iv) But there is one greater disadvantage. Suppose you have a new electric appliance, which needs a 15-A socket in an upstairs room.

To put in the new socket, it is necessary to put in new leads all the way back to the distribution box. Do you see why this will be an expensive business and what a disadvantage this is?

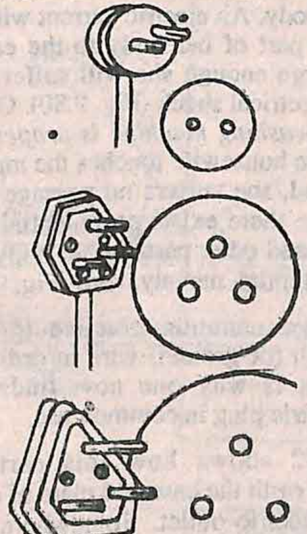


Fig. 9.74

The ring main system. This system in rapidly replacing the system described above. As its name implies, it consists of a ring circutit. This starts from the main fuse box, which usually has a 30-A fuse, runs round the main rooms of the house and back to the fuse box again, as shown in Fig 9.75

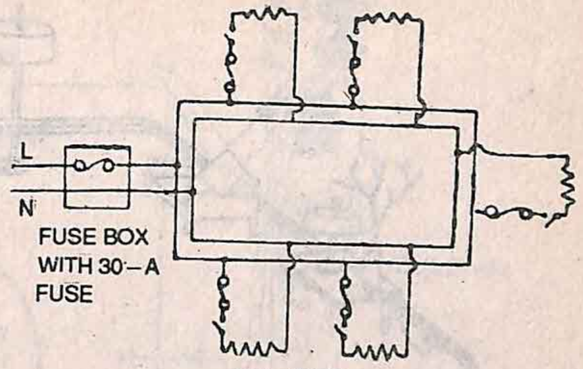


Fig. 9.75

There are two routes that the electricity can travel to any one appliance, so even though a 30A fuse is included, it is usually only necessary to have 15-A cable. It is possible to have plugs and sockets all of the same size, and the plugs used can have their own fuse (Fig. 9.76).

When a fuse blows, it only affects the single appliance concerned. It is easier to repair than grouping around at distribution box. Furthermore, it is very much easier to install a new power point without having to put in long leads all the way back to the distribution box. Of course, this assumes that the total load on the circuit will not exceed 30 A at any one time, that it will not be used for more than, say, three two-bar electric fires at one time. In large houses, it may be necessary to have more ring mains running round different parts of the house.

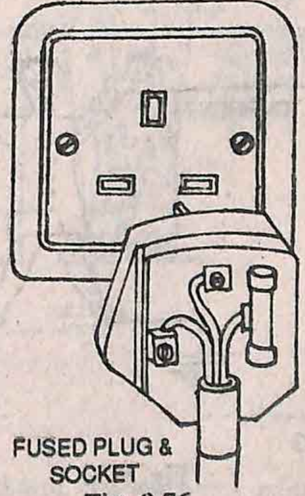


Fig. 9.76

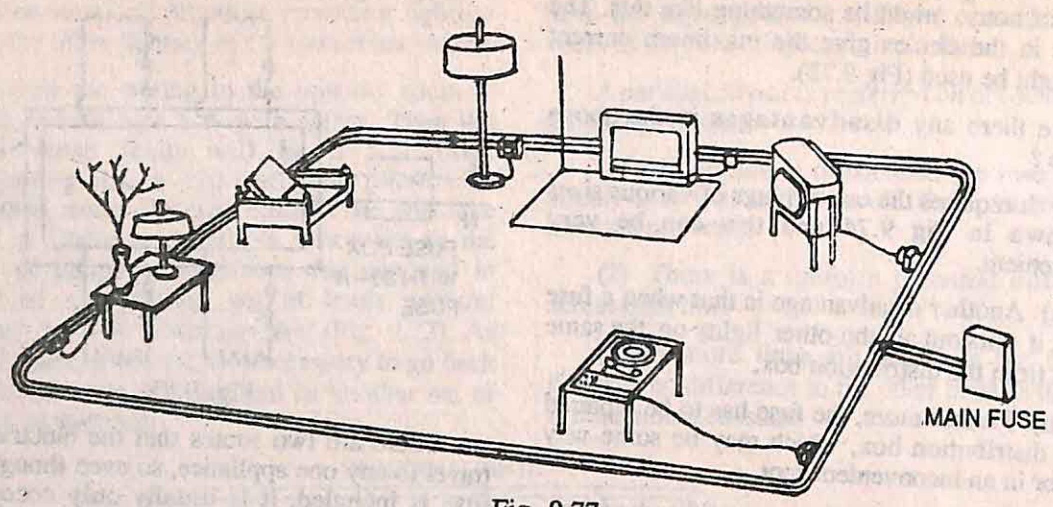


Fig. 9.77

Whatever system is used, it is necessary to have an earth wire as well as the live and neutral leads. The earth lead is connected to the third pin at all the sockets. The earth is shown in the drawing of a ring circuit around a living-room in Fig. 9.77.

9.28 EARTHING OF ELECTRICAL APPLIANCE ANDITS IMPORTANCE

In electrical terminology *earthing* or *grounding* is a conductor connected to the earth, the absolute potential of which is arbitrarily taken as zero. A common electrical symbol for earthing is shown in Fig 9.78.

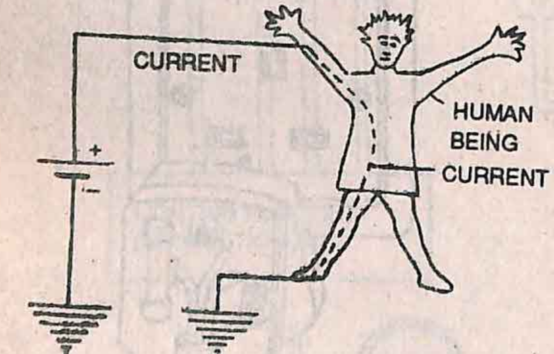


Fig. 9.78

An important aspect of earthing (or grounding) relates to safety. Take the case of an electric washing machine. Suppose some fault develops in the electric motor wiring (*e.g.*, breakdown of insulation), it is possible that the metal washing machine case could become connected to the electrical supply. The appliance will then become *live*. The unsuspecting house wife could by touching the machine inadvertantly, have a high potential difference established between different parts of her body. An electric current will then pass through this part of her body to the earth. If the current is large enough she will suffer a possible dangerous electrical shock (Fig. 9.80). On the other hand, if *the washing machine is properly earthed* then when the housewife touches the machine case with her hand, she suffers no passage of electric current, since there exists no potential difference between her and other parts of her body which are at ground potential, namely, zero (Fig. 9.81).

It is now common practice to provide a separate earth (or ground) wire in ordinary house wiring. That is why one now finds the three pronged electric plug in common use.

Fig 9.82 shows how this earth wire is employed to earth the case and plate of an ordinary household electric outlet. Somewhere this earth wire is ultimately connected to either a metal rod driven deep into the ground or simple to a water metal pipe, since the metal pipe usually travels well below ground level from the house to the main water supply.

The earthing of electrical appliance can also save the appliance from damage. If a short circuit occurs in the appliance, a large current will flow through the earth connected wire as it provides an

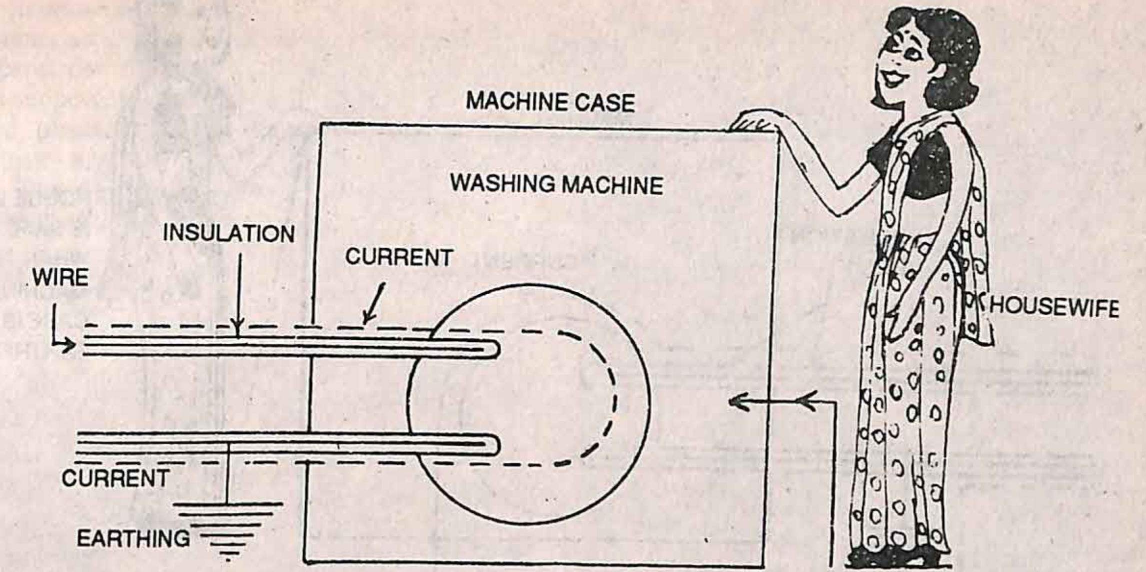


Fig. 9.79

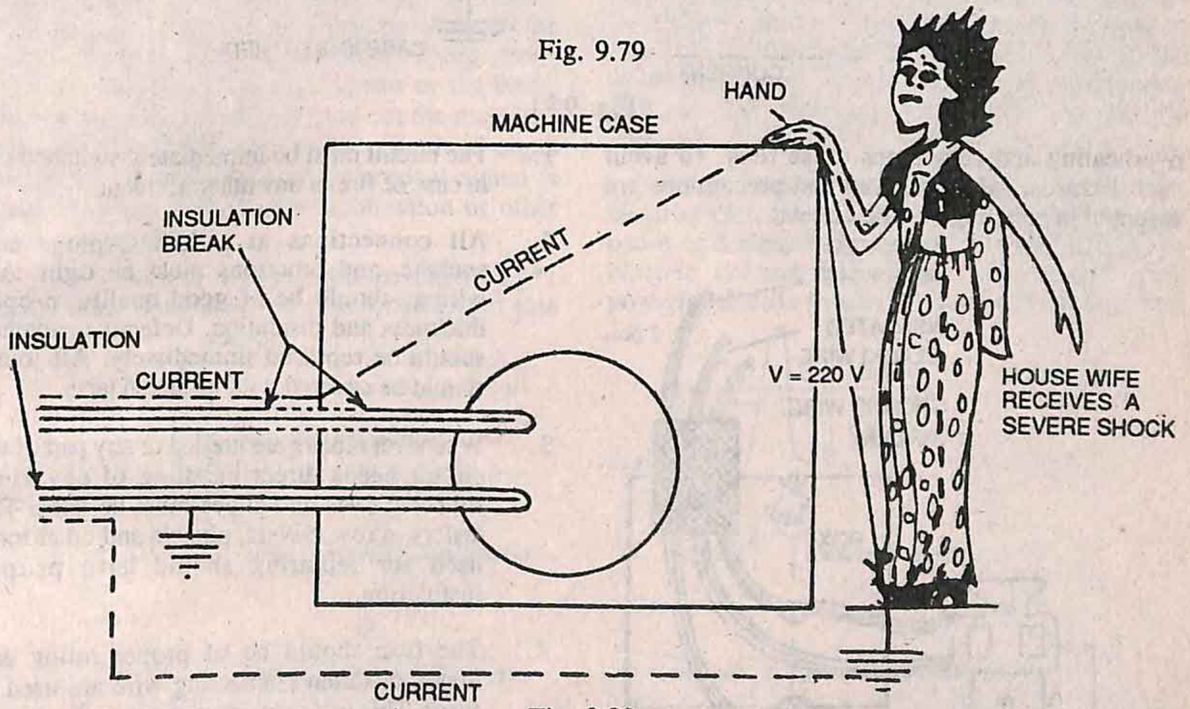


Fig. 9.80

easy path for the current. Due to this current the power supply would be cut and thus no damage would be done to the appliance.

9.29 HAZARDS OF ELECTRICITY

Electricity is one of the most important and convenient sources of energy available to us. However, it could be dangerous if certain precautions and safety measures are not observed while using.

You know that if you touch any point of an electric circuit you get a shock. Sometimes these shocks are so severe that they may kill a person. The flaws in electric circuits like loose connections, defective switches, damaged wire, short circuit or overloading can cause sparking or

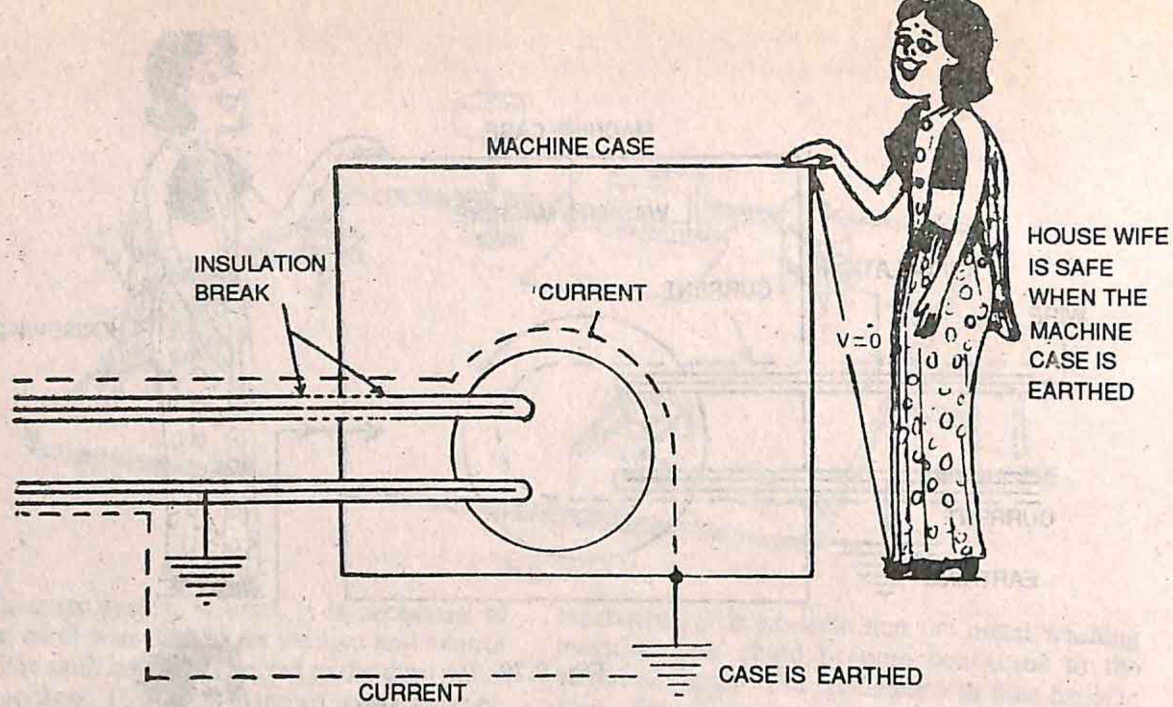


Fig. 9.81

overheating and sometimes cause fires. To avoid such hazards, safety devices and precautions are essential in handling electric circuits.

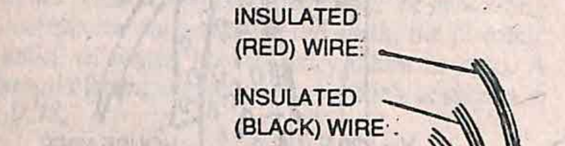


Fig. 9.82

We have seen how a fuse acts as a safety device. Some other essential precautions to be observed are :

1. The circuit must be immediately switched off in case of fire or any other accident.
2. All connections at switches, plugs and sockets, and junctions must be tight. All wiring, should be of good quality, proper thickness and insulation. Defective switches should be replaced immediately. All joints should be covered with insulated tape.
3. Whenever repairs are needed or any part of the circuit needs direct handling of any kind, rubber gloves and shoes must be used. The testers, screw drivers, pincers and other tools used for repairing should have proper instulation.
4. The fuse should be of proper rating and material. Often connecting wire are used as fuses. This is a dangerous practice. Such wire has too high a rating and will not protect you against a short circuit or overload.
5. The fuse and switches should always be connected to live wire in case of A.C. circuit. The earth wire must be used while using electrical appliances. One should not touch the metallic body of electric appliances like heaters or iron while they are switched on.

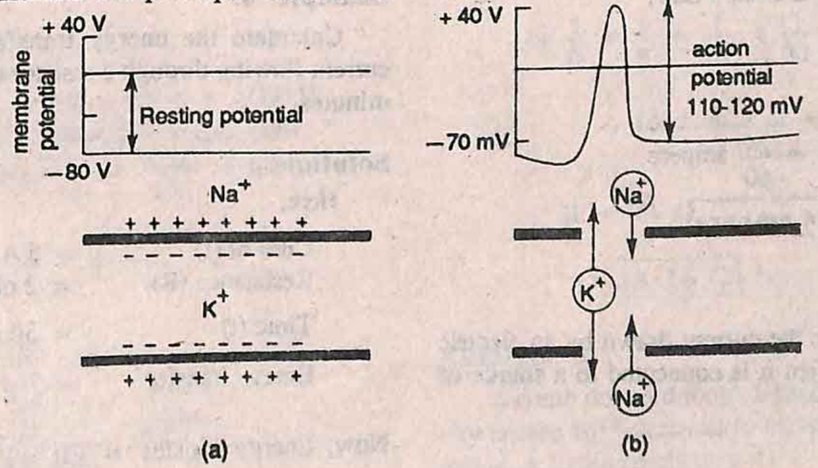
Despite all precautions, it is possible that someone accidentally contacts a live wire. If this happens, one should try to provide such a person with support of some non-conducting material like wood, plastic or rubber. One should never try to pull away a person who has contacted the live wire. The first step, of course, is to switch off the current at once.

9.30 ELECTRICITY IN THE ANIMAL BODY

As you will read in further chapters (Biology section) of this book, the nervous system in animals operates using electrical signals. Sensory organs such as the eye, ear, skin, nose and mouth register signals from the outside world. These signals are translated in the organs into electrical potentials using nerve cells or *neurons*. Neurons are specialised cells that even look like electrical wires. Sensory perception leads to the production of an electrical impulse, or action potential, in the neuron. This impulse is conducted along nerve fibres to the central nervous system or the brain. They process the signal and send out the response, again as electrical signals to the concerned organ for action. At this organ, the electrical signal is again translated into muscle contraction or other relevant response.

[How does a neuron produce electricity*? Figure 9.83 illustrates the principle behind this phenomenon. Normally, or in the resting state, the neuron is rich in K^+ ions inside and has a lower concentration of Na^+ than the outside medium. This concentration difference creates a p.d. between the outside and the cell of –0.070 V. The cell is negative with respect to the outside. When the action potential is triggered by the photoreceptor in the retina, the taste receptors of the mouth, the smell receptors of the nose, receptors of the skin or motor action of the muscle, the neuron "fires". A "gate" opens and lets Na^+ ions pour into the cell. This makes the cell electrochemically imbalanced and positive with respect to the outer medium. The potential changes from –0.070 V to + 0.040 V or a total change of about 0.110 – 0.120 V. This is the electrical impulse of the neuron. The impulse is caused by the operation of an ion pump system, called the Na^+, K^+ AT Pase enzyme system. In the wake of the impulse, K^+ are pumped out and the normal negative potential is restored. The impulse or action potential travels from one neuron to another through junctions called synpases at the speed of about 25 m/s, to the brain for processing and reaction. *The neuron is thus a biological electrochemical cell.*]*

Some organisms not only employ the electrochemical mechanism for their own use, but use it as a weapon for attack. The fish called the *electric eel* and the *electric* (ray) impart very powerful electric shocks to their victims and stun



(a)

RESTING

Na^+ excess outside

K^+ excess inside

Potential – 70 mV

Fig. 9.83

(b)

ACTION

Na^+ pours in

K^+ goes out

Potential + 40 mV

---

* Not to be evaluated. For further knowledge only

them before eating them. An electric eel is known to discharge 700 V and 1 ampere direct current electrical pulse at short intervals. This becomes possible due to the presence of over 6000 special cells called *electrocytes* in the eel's body, each of which can generate 0.1 V and all of which can discharge in synchrony. Unlike the neurons, an electrocyte is a flattened cell. Its upper face increases Na^+ entry upon firing while the lower face behaves normally. This leads to a discharge from the organism to the outside. Of course, the eel protects itself from its own discharge by the use of efficient insulators (fats, blubber) on its skin and beneath.

SOLVED EXAMPLES

Example 1.

A simple electric circuit has a 24 V battery and a resistor of 60 ohm. What will be the current in the circuit ? The resistance of the connecting wires is negligible.

Solution :

Given,

Resistance (R) = 60 ohm

Potential difference (V) = 24 volts

Current (I) = ?

According to Ohm's Law,

$$\frac{V}{I} = R$$

$$\therefore \quad I = \frac{V}{R} = \frac{24}{60} \text{ ampere}$$

$$= \boxed{\textbf{0.4 ampere}}$$

Example 2.

What will be the current drawn by an electric bulb of 40 W when it is connected to a source of 220 V ?

Solution :

Given,

Power (P) = 40 W

Potential difference (V) = 220 volts

Current (I) = ?

Since, P = VI

$$\therefore \; I = \frac{P}{V} = \frac{40}{220} \text{ A}$$

$$= \boxed{0.18 \text{ A}}$$

Example 3.

A current of 4 A flows through a 12 V car headlight bulb for 10 minutes. How much energy transfer occurs during this time ?

Solution :

Given,

Current (I) = 4 A

P. D. (V) = 12 volts

Time (t) = 10 minutes = $\frac{10}{60}$ h

Energy transfer = ?

Now, Energy transfer = V I t

$$= 12 \times 4 \times \frac{1}{6} \text{ Wh} = \textbf{8 Wh}$$

$$= \frac{12 \times 4}{1000 \times 6} \text{ KWh}$$

$$= \boxed{\textbf{0·008 kWh}}$$

Example 4.

Calculate the energy transferred by a 5 A current flowing through a resistor of 20 ohm for 30 minutes.

Solution :

Here,

Current (I) = 5 A

Resistance (R) = 2 ohm

Time (t) = 30 min. = $\frac{1}{2}$ h

Energy transfer = ?

Now, Energy transfer = $VIt = I^2 Rt \; (\because V = IR)$

$$= (5)^2 \times 2 \times \frac{1}{2} \text{ Wh}$$

$$= \textbf{25 Wh}$$

$$= \boxed{\textbf{0·025 kWh}}$$

Example 5.

An electrical heater is used on a 220 V supply and takes a current of 5 ampere.

(*a*) What is its power ?

(*b*) What is the cost of using the heater for *1h* if 1kWh costs 50 paise.

Solution :

Given,

Potential difference (V) = 220 volts
Current (I) = 5 amperes
Power (P) = VI = 220 × 5 watts
= **1100 watts**
= **1.1 kW**
Electric energy consumed = V I t
= 220 × 5 × 1 Wh
= 1.1 kWh
Cost = 1·1 × 50 = **55 paise**
= **Rs 0.55**

Example 6.

For a heater rated at 4 kW and 220 v, calculate

(*a*) the current,

(*b*) the resistance of the heater,

(*c*) the energy consumed in 2 hours, and

(*d*) the cost if 1 kWh is priced at 50 paise.

Solution :

Given,

Power (P) = VI = 4 kW = 4000 W
Potential difference (V) = 220 volts

(*a*) Current $(I) = \frac{P}{V} = \frac{4000}{220} = \mathbf{18{\cdot}18\ A}$

(*b*) Resistance of the heater

$$R = \frac{V}{I}$$

$$= \frac{220}{18{\cdot}18} \text{ ohms}$$

$$= \boxed{\mathbf{12{\cdot}10\ ohms}}$$

(*c*) Energy consumed in 2 h = V I t
= 220 × 18·18 × 2 Wh
= 7999·2 W h
= 7·9992 **kWh**

(*d*) Cost = 7·9992 × 50 paise
= 399·96 paise
= Rs 3·9996 = Rs 4.

Example 7.

Determine the potential drop across a 220 Ω resistor when it carries 450 mA.

Solution :

Given,

Resistance (R) = 220 Ω
Current (I) = 450 mA = 0·45 A
Potential drop (V) = ?

According to Ohm's Law,

$$V = I R$$

$$\therefore \quad V = 0{\cdot}45 \times 220$$

$$= \boxed{\mathbf{99\ V}}$$

Example 8.

Determine the total resistance of resistors R_1 = 5 Ω, R_2 = 15 Ω and R_3 = 20 Ω when they are connected (*a*) in series, (*b*) in parallel.

Solution :

(*a*) When resistance are connected *in series* :

$$R = R_1 + R_2 + R_3$$

$$= 5 + 15 + 20 \text{ ohms}$$

$$= 40 \text{ ohms}$$

(*b*) When resistances are connected *in parallel* :

$$\frac{I}{R} = \frac{I}{R_1} + \frac{I}{R_2} + \frac{I}{R_3}$$

$$\text{or } \frac{I}{R} = \frac{I}{5} + \frac{I}{15} + \frac{I}{20}$$

$$= \frac{12 + 4 + 3}{60} = \frac{19}{60}$$

$$\therefore \quad R = \frac{60}{19}\ \Omega$$

$$= \boxed{\mathbf{3{\cdot}16\ \Omega}}$$

Example 9.

A comb drawn through a person's hair on a dry day causes 10^{12} electrons to leave the person's hair and stick to the comb.

(*a*) Is the force between the comb and the hair attractive or repulsive ?

(*b*) What is the magnitude of this force when the comb is 1.0 m from the person's hair ? Electronic charge = $-1{\cdot}60 \times 10^{-19}$ C.

Solution :

(*a*) The force is *attractive* because the charge on the comb is negative and that on the hair is positive. Unlike charges attract.

(*b*) From Coulomb's Law, we have

$$F = K\frac{q_1q_2}{r^2} \text{ where } K = 9{\cdot}0 \times 10^9\, Nm^2/C^2$$

$$= \frac{(9{\cdot}0 \times 10^9)\,(10^{12})\,(+\,1{\cdot}6 \times 10^{-19}) \times (10^{12})(-\,1{\cdot}6 \times 10^{-19})}{(1{\cdot}0)^2}$$

$= -\,2{\cdot}3 \times 10^{-4}\, N$; the *minus sign* means that the force is *attractive.*

Example 10.

(*a*) The force required to give a 1000 kg car an acceleration of $2{\cdot}5$ m/s^2 is $2{\cdot}50 \times 10^3$ N. What would the charge have to be on two small spheres 10 m apart to produce the same force between the spheres. If we assume that both spheres have the same charge ?

(b) If the charge on each sphere is negative, how many excess electrons are there on each sphere ? Electronic charge = 1.60×10^{-19} C.

Solution :

(*a*) From Coulomb's law, with $q_1 = q_2 = q$ (say), we have

$$F = K\,\frac{q_1q_2}{r^2} = K\frac{q^2}{r^2}$$

where $K = 9.0 \times 10^9$ Nm^2/C^2.

$$\text{Hence } q^2 = \frac{Fr^2}{K}$$

$$= \frac{(2{\cdot}50 \times 10^3)(1{\cdot}0)^2}{9{\cdot}0 \times 10^9} = 2{\cdot}77 \times 10^{-7}\ \mathrm{C}^2$$

and so $q = 5{\cdot}26 \times 10^{-4}$ C = 526 μC.

Two charges of 526 μC at a distance of 1 m apart would, therefore, produce this relatively large force of $2{\cdot}5 \times 10^3$ N.

(*b*) The charge on the electron is $1{\cdot}60 \times 10^{-19}$ C. Hence the number *n* of electrons in 526 μC is

$$n = \frac{526\mu\mathrm{C}}{1{\cdot}60 \times 10^{-19}}\ \text{C/electron}$$

$$= \frac{526 \times 10^{-6}\mathrm{C}}{1{\cdot}60 \times 10^{19}}\ \text{C/electron}$$

$$= \mathbf{3.\ 29 \times 10^{15}\ electrons}$$

Example 11.

A 12-V storage battery drives 50 C of charge through a light bulb in 1 minute.

(*a*) How much work has been done by the battery ?

(*b*) What is the electric power ?

Solution :

(*a*) Since the voltage, or potential difference, is the *work done per unit charge*, or

$$V_{\mathrm{AB}} = \frac{W}{q}$$

We have, $W = qV_{\mathrm{AB}}$

$= (50\ \mathrm{C})(12\ \mathrm{V})$

$= \boxed{600\ \mathrm{J}}$

(*b*) Since power is the rate at which work is done,

$$P = \frac{W}{t}$$

and so $\mathrm{P} = \dfrac{600\ \mathrm{J}}{60\ \mathrm{s}}$

$= 10$ J/s

$= \boxed{10\ \mathrm{W}}$

Hence, the power delivered by the storage battery is the same as that consumed by a 10-W light bulb.

Example 12.

An electron in a TV set is accelerated toward the screen by a voltage of 1000 V. The screen is 35 mm from the electron source.

(*a*) How much work is done by the voltage in accelerating the electron ? xyz

(*b*) What is the speed of the electron when it strikes the screen ?

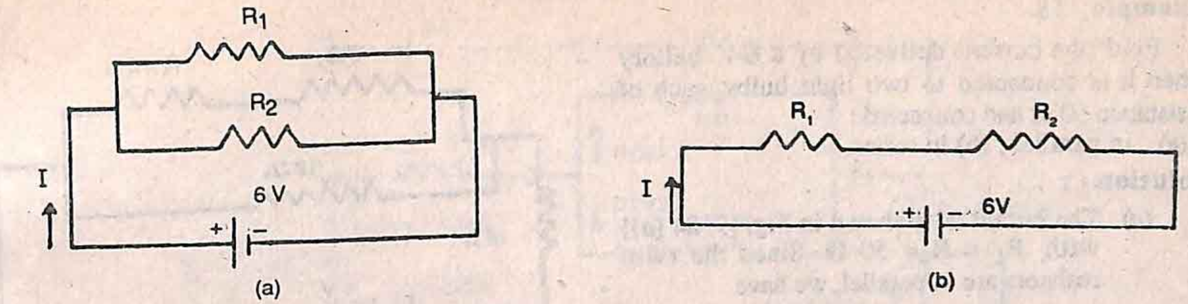


Fig. 9.84

Electronic charge = $1{\cdot}6 \times 10^{-19}$ C; mass of the electron = $9{\cdot}1 \times 10^{-13}$ kg.

Solution :

(*a*) Since the work done per unit charge by the field is

$$\frac{W}{q} = V,$$

we have $W = qV$

$$= (1{\cdot}6 \times 10^{-19})(1000) \text{ J}$$

$$= \boxed{1{\cdot}6 \times 10^{-16} \text{ J}}$$

(*b*) By the principle of conservation of energy all this work must be converted into kinetic energy of the electron, hence

$$\text{K.E.} = \frac{1}{2} mv^2 = 1{\cdot}6 \times 10^{-16} \text{ J}$$

and so

$$v = \left[\frac{2(1{\cdot}6 \times 10^{-16}) \text{ J}}{9.1 \times 10^{-31} \text{ kg}}\right]^{\frac{1}{2}}$$

$$= \boxed{1.9 \times 10^{7} \text{ ms}^{-1}}$$

Note that the distance between source and screen is of no importance here. The crucial factor is the voltage between source and screen.

Example 13.

A current of 15 A is maintained for 30 min through an electrolytic cell containing $CuSO_4$. What is the amount of the charge flowing through the cell ?

Solution :

The amount of the charge flowing through the cell is

$$Q = I\,t$$

$$= 15 \times 30 \times 60 \text{ C}$$

as $I = 15$ A and $t = 30 \times 60$ seconds

$\therefore$ $Q = 2{\cdot}7 \times 10^4$ C.

Example 14.

The resistance of a graphite rod is 3.0×10^{-1} Ω.

(*a*) What voltage must be applied across the two ends of the rod to produce a current of 10A through the rod ?

(*b*) If the required voltage is supplied by a battery which delivers current for 10 min, how much work does the battery do ?

Solution :

(*a*) From Ohm's Law,

$$V = IR$$

$$= 10 \times 3.0 \times 10^{-1} \text{ volt}$$

$$= \boxed{3 \text{ V}}$$

(*b*) Since, work done = $W = QV = 3Q$, and $Q = It = 10 \times 10 \times 60 \text{ C} = 6 \times 10^3$ C

We have $W = 3 \times 6 \times 10^3$ J

$$= \boxed{1.8 \times 10^4 \text{ J}}$$

Example 15.

Find the current delivered by a 6-V battery when it is connected to two light bulbs, each of resistance 50 Ω and connected :

(a) in parallel ; (b) in series.

Solution :

(*a*) The circuit is as shown in Fig. [9. 84 (*a*)] with $R_1 = R_2 = 50\ \Omega$. Since the two resistors are in parallel, we have

$$\frac{1}{R} = \frac{1}{50} + \frac{1}{50} = \frac{2}{50}$$

or $R = 25\ \Omega$.

Hence $I = \frac{V}{R} = \frac{6}{25} = \boxed{0.24A}$

(*b*) In this case, the circuit is as in Fig. 9·84 (*b*) and

$$R = R_1 + R_2$$
$$= 50 + 50 = 100\ \Omega$$

Then $I = \frac{V}{R} = \frac{6}{100} = \boxed{0{\cdot}060\ A}$

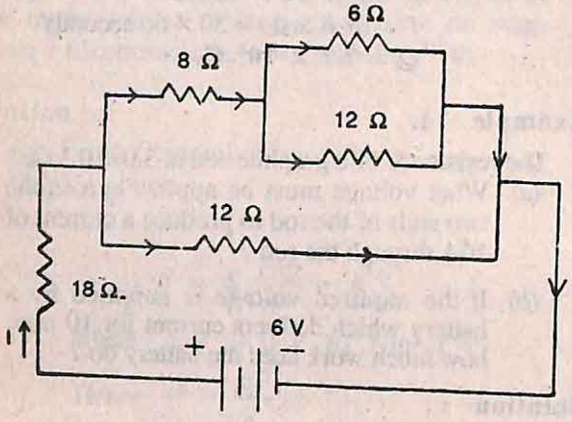


Fig. 9.85

***Example 16.**

(a) In the circuit of Fig 9·85, find the current I in the 18 Ω resistor. The terminal voltage of the battery is 6·0 V.

(b) Find the currents flowing in the individual branches of the circuit.

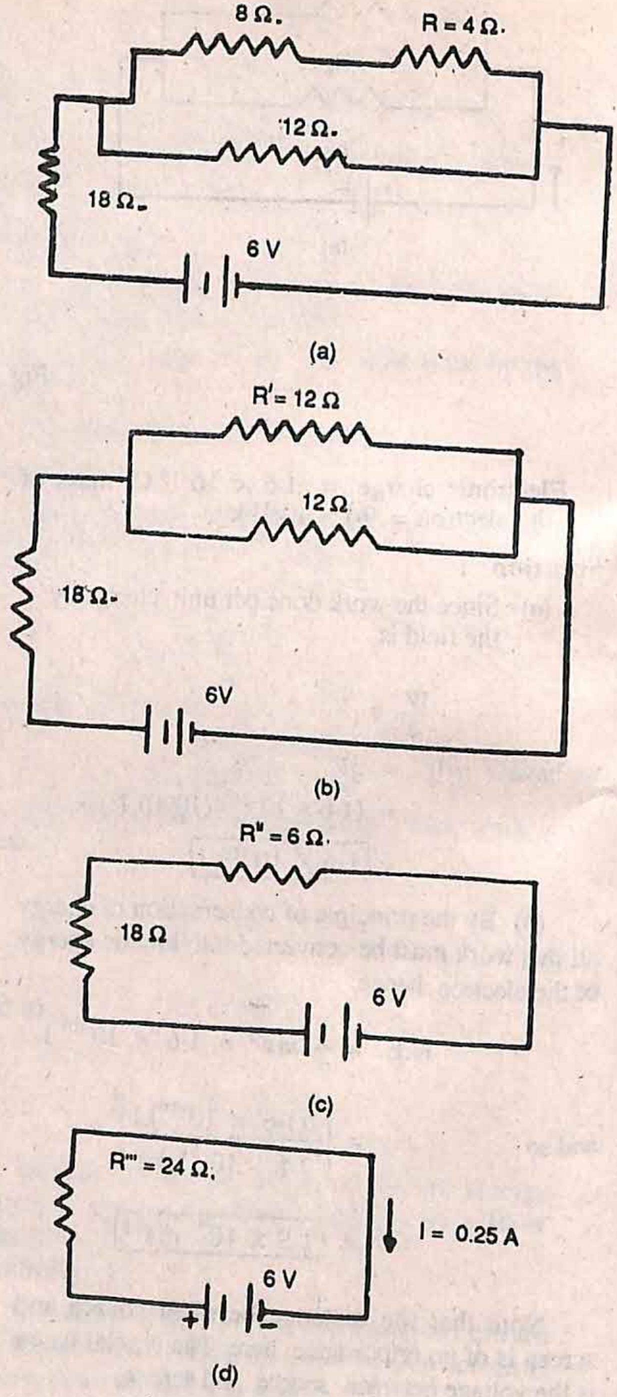


Fig. 9.86

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* Harder Problem

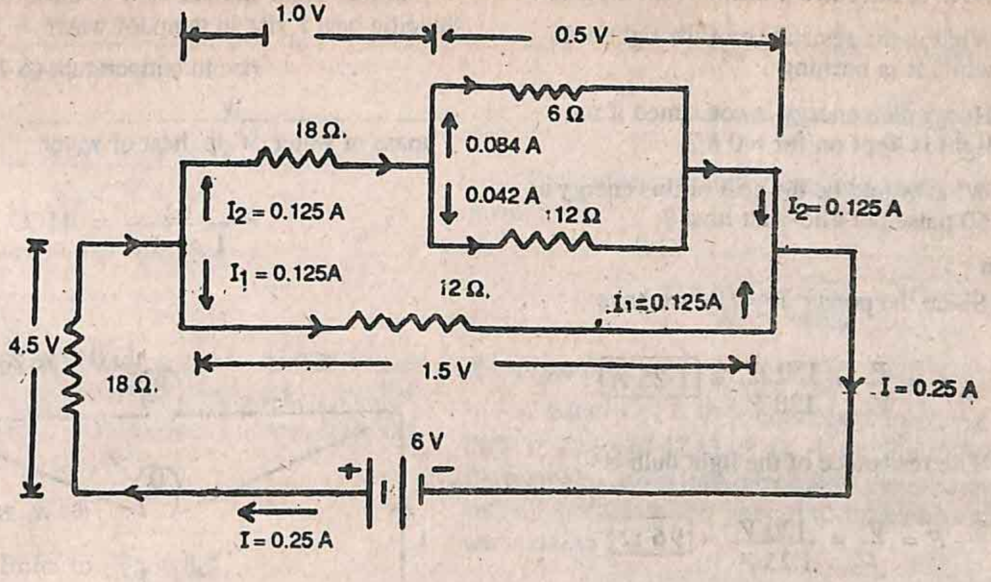

Fig. 9.87

Solution :

(*a*) Here we must find the equivalent resistance of the circuit. In such complicated circuits the best approach in applying the laws for combining resistances in series and in parallel is to start with the innermost combination of resistances. This is the combination of the 6 Ω and the 12 Ω resistors in parallel. We find

$$\frac{1}{R} = \frac{1}{6} + \frac{1}{12} = \frac{1}{4}$$

or $R = 4\,\Omega$

We can then add this in series with the 8 Ω resistor to obtain

$$R' = 8 + R = 8 + 4 = 12\,\Omega$$

Next we must combine R' with the 12 Ω resistor in parallel to obtain R'' We have

$$\frac{1}{R''} = \frac{1}{R'} + \frac{1}{12} = \frac{1}{12} + \frac{1}{12} = \frac{1}{6}$$

and so $R'' = 6\,\Omega$. This must then be combined in series with the 18 Ω resistor to yield a final equivalent resistance R'''.

We have, $R''' = 18 + 6$
$= 24\,\Omega$.

Our circuit has now been reduced to a voltage of 6·0 *V* driving a current through an equivalent resistance of 24 Ω. Hence, from Ohm's law,

$$I = \frac{V}{R} = \frac{6{\cdot}0}{24} = \boxed{0{\cdot}25\ A}$$

The steps in this process of combining resistances are illustrated in Fig. 9.86.

(*b*) Since $R' = 12\,\Omega$ and is in parallel with another 12 Ω resistor, the 0·25 *A* current must split in two, with half going through the 12 Ω resistor and half going through the other branch. The 0·125 *A* going through the upper branch must also split so that twice as much current goes through the 6 Ω resistor as, through the 12 Ω resistor, *since the voltage across the two is the same*. Hence

$\boxed{0.042\ A}$ goes through the 12 Ω resistor

and

$\boxed{0.084\ A}$ through the 6 Ω resistor.

The results are shown in Fig. 9.87.

Example 17.

A 150 *W* light bulb is connected to a 120 *V* line.

(*a*) What is the current drawn from the line ?

(*b*) What is the resistance of the light bulb while it is burning ?

(*c*) How much energy is consumed if the light is kept on for 6·0 *h* ?

(*d*) What would be the cost of this energy at 50 paise per kilo-watt-hour ?

Solution :

(*a*) Since the power $P = IV$, we have

$$I = \frac{P}{V} = \frac{150\ W}{120\ V} = \boxed{1{\cdot}25\ A}$$

(*b*) The resistance of the light bulb is

$$R = \frac{V}{I} = \frac{120\ V}{1.25\ A} = \boxed{96\ \Omega}$$

(*c*) $W = Pt$ where W is energy consumed.

$$= (150\ W)\ (6{\cdot}0\ h) = 900\ Wh = \boxed{0{\cdot}90\ kWh}$$

(*d*) cost = 0·90 × 50 = 45 paise = **Rs 0·45**

Example 18.

A 50 Ω resistor is attached to a 120 *V* circuit Fig. 9.87 and immersed in 1·5 kg of water. If the current drawn from the line for 15 min, what is the increase in temperature of the water, presupposing that all the electric energy goes into heating water ? Specific heat of water = 1 kcal/kg °C and 1 kcal = 4·18 × 10³ J.

Solution :

The current drawn from the circuit is

$$I = \frac{V}{R} = \frac{120}{50} = \boxed{2{\cdot}4\ A}$$

The electric energy going into heating the water is then

$W = I^2 Rt$ here $R = 50\ \Omega$ and $t = 15 \times 60\text{s}$

$$= (2{\cdot}4)^2 \times 50 \times (15 \times 60) = 2{\cdot}6 \times 10^5\ \text{J}$$

$$= \frac{2{\cdot}6 \times 10^5}{4{\cdot}18 \times 10^3}\ \text{kcal}$$

$$= 62\ \text{kcal}$$

Since, Heat gained = W = mass of water × Specific heat × rise in temp. of water

∴ rise in temperature (ΔT)

$$= \frac{W}{\text{mass of water} \times \text{sp. heat of water}}$$

$$= \frac{62}{1 \times 1{\cdot}5} = 41^\circ\text{C}$$

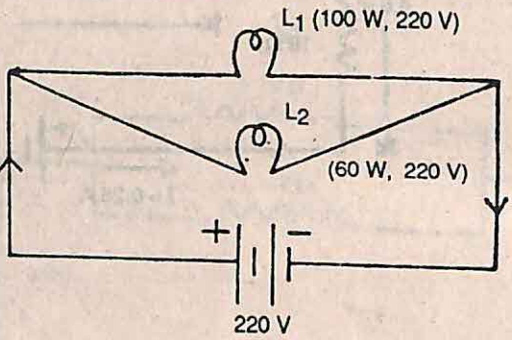

Fig. 9.88

Example 19.

A heater coil connected to 220 *V* has a resistance of 150 Ω. How long will it take this coil to heat 1 kg of water from 20°C to 60°C, assuming that all heat is taken up by water ?

Specific heat of water = 1 kcal/(kg°C) and 1 kcal = 4·20 × 10³ *J*.

Solution :

The current drawn from the circuit is

$$I = \frac{V}{R} = \frac{220}{150} = 1{\cdot}47\ A$$

The electrical energy going into heating the water for *t* seconds is then

$$W = I^2 R\, t$$

$$= (1.47)^2 \times 150 \times t \text{ joule}$$

$$= \frac{(1{\cdot}47)^2 \times 150 \times t}{4{\cdot}20 \times 10^3}\ \text{kcal}$$

Since, Heat gained = W = mass ofwater × specific heat of water × rise in temperature

$$\therefore \quad \frac{(1{\cdot}47)^2 \times 150 \times t}{4{\cdot}20 \times 10^3} = 1 \times 1 \times 40$$

$$\therefore \quad t = \frac{40 \times 4.20 \times 10^3}{(1.47)^2 \times 150} \text{ second}$$

$$= 518{\cdot}3 \text{ second.}$$

Example 20.

Two lamps, one rated at 100 W at 220 V and the other 60 W at 220 V are connected in parallel to a 220 V supply. What current is drawn from the supply line ?

Solution :

Refer to (Fig. 9.88)

For lamp L_1

Power = P_1 = 100 W

Voltage = V_1 = 220 V

$\therefore$ Current drawn = $I_1 = \frac{P_1}{V_1} = \frac{100}{220} = \frac{5}{11}$ A

$\therefore$ Resistance (R_1) of the lamp

$$= \frac{V_1}{I_1} = \frac{220}{5/11} = 484\ \Omega$$

For Lamp L_2

Power = P_2 = 60 W

Voltage = V_2 = 220 V

$\therefore$ Current drawn = $I_2 = \frac{P_2}{V_2} = \frac{60}{220} = \frac{3}{11}$ A

Hence, resistance (R_2) of the lamp

$$= \frac{V_2}{I_2} = \frac{220}{3/11} = \frac{2420}{3}\ \Omega$$

Since the two lamps are connected in parallel, their equivalent resistance (*R*) is given by

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{1}{484} + \frac{3}{2420} = \frac{8}{2420}$$

$$\therefore \quad R = \frac{2420}{8} = \frac{605}{2}\ \Omega$$

The current drawn from the supply line is given by

$$I = \frac{V}{R} = \frac{220}{605/2} = 0{\cdot}727\ A$$

Example 21.

A battery of 6 V is connected in series with three resistors of 12 Ω, 6 Ω, 4 Ω (Fig. 9.89). Is the current passing through each of the resistors the same ? Calculate the potential difference across each resistor ?

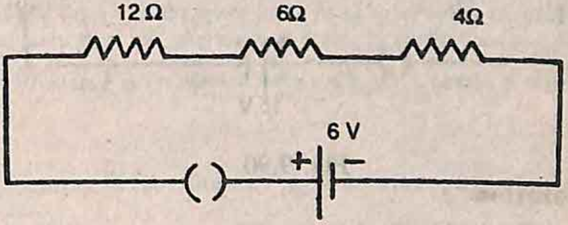

Fig. 9.89

Solution :

Yes ; since the three resistors and the battery are connected in *series* so the current passing through each of the resistors *will be the same.*

Total resistance (*R*) in the circuit

= 12 + 6 + 4 = 22 Ω

Total Potential difference (*V*) = 6 V

According to Ohm's law, current (*I*) in the circuit is given by

$$I = \frac{V}{R} = \frac{6}{22}\ A = 0{\cdot}27\ \text{A}$$

P.D. across 12 Ω = current × resistance

$$= \frac{6}{22} \times 12 = 3{\cdot}27\ \text{V}$$

Similarly,

$$\text{P.D. across } 6\ \Omega = \frac{6}{22} \times 6 = \mathbf{1{\cdot}64\ V}$$

$$\text{P.D. across } 4\ \Omega = \frac{6}{22} \times 4 = \mathbf{1{\cdot}09\ V}$$

Example 22.

In the circuit shown in the Fig. 9.90 , calculate

(*a*) the current flowing through the arms AB, *AC and CDE ;*

(*b*) the potential difference across *AB*, *CD and DE*,

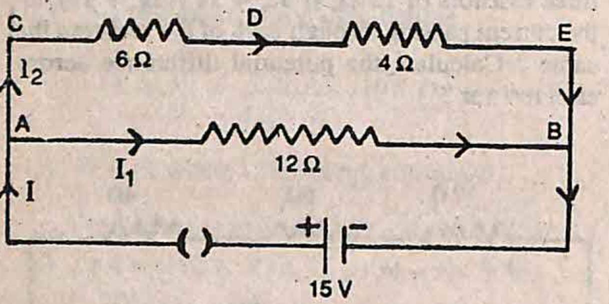

Fig. 9.90

Solution :

Equivalent Resistance of the arm *CDE* = 6 + 4 = 10 Ω (resistances in series).

Since the resistances 10 Ω and 12 Ω are *in parallel*, so the equivalent resistance (*R*) of the whole circuit is given by

$$\frac{1}{R} = \frac{1}{10} + \frac{1}{12} = \frac{11}{60}$$

$$\text{or} \quad R = \frac{60}{11}\ \Omega$$

According the Ohm's law, current (*I*) in the circuit is given by

$$I = \frac{V}{R} = \frac{1{\cdot}5}{\frac{60}{11}} = \frac{1{\cdot}5 \times 11}{60} = 0{\cdot}275\ \text{A}$$

(*a*) At the junction *A* (Fig. 9.90), the current *I* gets divided into two parts I_1 and I_2 so that $I = I_1 + I_2$. Let I_1 flows through the arm *AB* and I_2 flows through the arm *CDE*. Since the arms *AB* and *CDE* are connected *in parallel* so the potential difference across the arms *AB* and *CDE* each is *the same.*

Hence,

$$12 \times I_1 = 10 \times I_2 \quad (\text{Ohm's law } i.e., V = IR)$$

$$\therefore \quad \frac{I_1}{I_2} = \frac{10}{12}$$

$$\text{or} \quad \frac{I_1}{I_1 + I_2} = \frac{10}{10 + 12}$$

$$\text{or} \quad \frac{I_1}{I} = \frac{10}{22}$$

$$\therefore \quad I_1 = \frac{10}{22} \times I = \frac{10}{22} \times 0{\cdot}275 = \mathbf{0{\cdot}125\ A}$$

The current flowing through the arm *AB* = **0·125 A**

$$\text{Now, } I_2 = I - I_1 = 0{\cdot}275 - 0{\cdot}125 = \mathbf{0{\cdot}15\ A.}$$

Thus the current flowing through the arms *AC* and *CDE* = **0·15 A** as they are connected *in series.*

(*b*) P.D. across the arm *AB*
= current × resistance
= 0·125 × 12 = **1·5 V**

P.D. across the resistor
CD = current × resistance
= 0·125 × 6 = **0·9 V**

P.D. across the resistor
DE = 0·15 × 4 = **0·6 V**

SUMMARY

1. **Simplest method of producing an electric charge is to rub two bodies with each other. Ebonite or plastic objects rubbed with wool and glass rubbed with silk, acquires the ability to attract small objects and the bodies showing this effect are said to be charged.**

2. There exist only tow kinds of electrical charges. The charge acquired by a glass rod rubbed with silk is, by convention, called *positive charge* and that on an ebonite rod rubbed with wool is called *negative charge.*

3. Like charges repel each other while unlike charges attract each other.

4. According to the principle of conservation of electric charge, the electric charge is always conserved. It can neither be created nor destroyed. It can only be transferred from one material to another.

5. The materials in which charges move easily are called *Conductors* and those in which charges seem to be bound as *insulators.*

6. *Coulomb's Law.* The force of attraction or repulsion between two charged bodies carrying charges q_1 and q_2 and separated by a distance r in vacuum (or air) is given by

$$\boxed{\vec{F}=K\frac{q_1q_2}{r^2}}$$

where K is constant of proportionality and is equal to 9×10^9 Nm^2/C^2
In magnitude,

$$\boxed{F=K\frac{q_1q_2}{r^2}}$$

7. The unit of electric charge is a *coulomb* (C). If two equal and similar charges, placed 1*m* apart, repel each other with a force of 9×10^9 N, each charge is of almost 1 coulomb.

8. A charged body can be regarded as surrounded by a field of force *i.e.*, the space in its neighbourhood is changed in such a way that another charged body, when present in this region, will experience a force. In general *electric field intensity* $\vec{E}(r)$ at a point $\vec{r}$ is defined such that $q\vec{E}(r)=\vec{F}(r)$ where $\vec{F}$ is the electric force acting on a charge q placed at r.

From Coulomb's law it follows that the electric field intensity $\vec{E}(r)$ at a distance r from the point charge q situated at the origin is

$$\boxed{\vec{E}(r)=\frac{Kq}{r^2}}$$

The direction of the vector $\vec{E}$ is that of the force on the *unit positive charge*. In S.I. units, the electric field is expressed in newton/coulomb. The charge q is the source of the electric field and is called the *source charge* and the charge which feels the influence of the field is known as the *test charge*. A test charge is taken to be *vanishingly small* so that it does not alter the field to be measured by any appreciable extent.

When there is more than one charge producing the field, we use the superposition principle to calculate the resultant field intensity at a given point.

9. The path traced by a test charge free to move under the effect of an electric field is called an *electric line of force.* Thus a line of force is a curve so drawn that a tangent to it at any point gives the direction of the electric field at that point.

By convention, electric lines of force originate from a positively charged body and end at the negatively charge one.

No two lines of force intersect each other.

10. A charge in an electric field experiences a force and in response to this the charge moves, work is done by the source of the field. If, however, the charge is moved *against* the force, work is done by an outside agency.

When a charge in an electric field moves from one point to another, the two points are said to differ in *electric potential*. We define the *electric potential difference* between the two points *A* and *B* as the work done to move a unit charge from *A* and *B*.

$$\text{Potential difference (V)} = \frac{\text{work done (W)}}{\text{charge (Q)}}$$

or $\boxed{W = VQ}$

The unit of electric potential is *volt*. Potential is a *scalar* quantity.

One volt is the potential difference between two points in an electric field when 1 joule of work is done to move a charge of 1 coulomb from a less positive to a more positive point.

$$\boxed{1\ \text{volt} = \frac{1\ \text{joule}}{1\ \text{coulomb}}}$$

11. Flow of electric charge is called an *electric current*. Electric current flows when there is an electric potential difference and to keep an electric current flowing through a conductor, it is obviously necessary *to maintain the potential difference* between its ends.

The electric current is the amount of charge passing through a given point in one second.

$$I = \frac{Q}{t}$$

Current is a *scalar quantity*. The unit of electric current is *ampere (A)*.

$$1\ \text{ampere} = \frac{1\ \text{coulomb}}{1\ \text{second}}.$$

One electron carries a charge of $1{\cdot}6 \times 10^{-19}$ C and a current of one ampere corresponds to a flow of $6{\cdot}3 \times 10^{18}$ electrons/second. In fact there is a *drift* of so many electrons (not necessarily involving the same) every second from one end of the wire to the other.

12. The property of a conductor which affects the flow of current in it is called its *resistance*. It is expressed in volt/ampere, or *ohm* (symbol Ω). A conductor possessing a certain resistance is usually called a *resistor.*

13. *Ohm's Law.* The current flowing through a conductor is directly proportional to the potential difference across its ends provided the physical conditions of the conductor *e.g.*, density, temperature, etc., remain constant.

Mathematically; $\frac{V}{I} = R$ or $V = IR$

14. *Resistances in series :*

$$R = R_1 + R_2 + R_3 + \ldots\ldots$$

The value of the equivalent resistance *R* is equal to the sum of the resistances in series.

Resistances in parallel :

$$\boxed{\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots\ldots}$$

The reciprocal of the equivalent resistance is the sum of the reciprocals of the resistances.

15. The resistance of a given wire depends upon

(*i*) the material of the wire,

(*ii*) the length of the wire, and

(*iii*) the area of cross-section of the wire.

Expressed mathematically, it implies that

$$R = \rho = \frac{l}{A}\ \textit{where}\ \rho = \text{resistivity of the material.}$$

16. *Resistivity* (or *specific resistance*) of a material is defined as the resistance of a cube of the material of side 1 m when current flows perpendicular to opposite faces. It is expressed in *ohm m.*

17. Amount of *heat generated* $H = \frac{I^2Rt}{4{\cdot}18}$ cal $= I^2$ Rt joule $= VIt$ joules $= \frac{V^2t}{R}$ *joules*

Electric power $(P) = \frac{W}{t} = I^2R = VI$ *watt*

kilo-watt-hour (kWh) is the unit of energy.

$$1\ \text{kWh} = 3{\cdot}6 \times 10^6\ \text{J}$$

18. A bar magnet attracts iron filings more strongly near its free ends. These ends are called the *poles*. If a bar magnet is suspended in such a way that it is free to rotate in a horizontal plane, it takes the north-south direction. The end which points towards the north is called the north pole and the end which points towards the south is called the south pole.

19. Like poles repel and the unlike poles attract each other. The force of attraction or repulsion acts along the line joining the two poles, and is inversely proportional to the square of the distance between them.

If we break a magnet into two or more similar pieces, even the smallest possible magnet has both north and south poles. We cannot obtain isolated magnetic poles.

20. A magnet generates a *magnetic field* in the space surrounding it. The direction of the magnetic field at any point is taken as the direction of the resultant force acting on a hypothetical isolated north pole placed there. A magnetic field is conveniently described by sketching the magnetic lines of force. The magnitude of the magnetic field is proportional to the force experienced by that isolated north pole.

21. Magnetic lines of force have certain characteristics or properties.

22. An infinitely long straight conductor carrying a current (I) produces a magnetic field around it.

The direction of the magnetic field is given by *right-hand rule*. If we imagine holding current carrying wire in our right-hand, such that the thumb is stretched along the direction of the current, then the fingers will wrap around in the direction of the magnetic field.

23. S.I. unit of magnetic field is *tesla* (*T*). It is a fairly big unit. Magnetic field of the earth near the surface is about $0.3 \times 10^{-4}\ T$.

Magnetic field $\vec{B}$ is a vector

24. *Force on a current-carrying conductor of length l in a magnetic field.*

Magnitude : $F = BIl$ where B is in tesla (T) = 1IN/(A.m.).

Direction : (Fleming's Left Hand Rule). Stretch the first finger, the middle finger and the thumb of your left-hand in such a way that they are mutually at right angles to each other. If the first finger represents the direction of the magnetic field, the middle finger represents the direction of the current in the conductor, then, the thumb will represent the direction of motion of the conductor.

Electrical motor is a device which converts electrical energy into mechanical energy. It is based on the fact that a current carrying conductor, when placed in a magnetic field, experiences a mechanical force.

25. A solenoid consists of many circular turns of wire wrapped in the shape of a cylinder. Since the current in each circular turn has the same direction, the field due to each turn adds up, giving a fairly strong resultant field inside a solenoid.

In fact, the magnetic field due to a long solenoid has all the properties of the field produced by a bar magnet — the ends of the solenoid acting as the *poles*.

26. *Galvanometer* is an instrument used for detecting currents flowing in a circuit. Its working is based on the fact that a current-carrying conductor placed in a magnetic field experiences a force perpendicular to both, the current and the field. It is so constructed that the deflection is proportional to the current.

Ammeter : It is a device which is used for measuring a current in a circuit. It has a very low resistance as compared to the total resistance of the circuit. It is connected *in series* in the circuit as it produces a negligible change in the value of the current.

Ammeter is a modified moving coil galvanometer. The scale is graduated in *amperes;* with its zero at one end.

Voltmeter : It is an instrument used for measuring potential difference. It must be placed *in parallel* with the circuit and it must have high resistance.

27. The phenomenon of production of an electric current in a circuit by the help of the magnetic field is called *electromagnetic induction*. The direction of the induced current is given by *Fleming's right-hand rule* : Stretch the fore-finger, the middle finger and the thumb of your right-hand in such a way that they are mutually at right angles to each other. If the fore-finger represents the direction of the magnetic field, the thumb represents the direction of motion of the conductor in the magnetic field, then the middle finger will represent the direction of the induced current in the conductor.

28. An *electric generator* is a device which *converts mechanical energy into electrical energy*. A current which charges direction after equal intervals of time is called an *alternating current* (A.C.). A current that flows in the same direction is called a *direct current* (D.C.). A device which produces A.C. is called A.C. generator or an A.C. dynamo. A device which produced D.C. is called D.C. generator or D.C. dynamo.

In India, the A.C. changes direction after every 1/100 second *i.e.*, the frequency of A.C. is 50 hz.

The principle of a generator is used in electric power plants to generate large amounts of electrical energy for use in industry and in homes.

A.C. can be transmitted over long distances without much energy loss.

29 In our homes we receive supply of electric power through mains from electric poles. One of the wires in this supply, usually with red insulation on it, is called *live wire* (or positive). Another wire with black insulation is called *neutral wire* (or negative). Potential difference between them, in India, is 220 volts. At the meter-board in the house these wires go into the watt-hour-meter through a *main-fuse*. Then through a *main switch* they are connected to line wires in the home.

Various appliances in the house are then connected to these line wires, each with its independent switch. In order that each appliance gets equal voltage, *they are connected in parallel with each other*. This also ensures that one is switched 'on' or 'off', other are not affected.

The watt-hour-meter measures the sum total of energy consumed in all the appliances because currents of all the appliances pass through it.

Each pair of live wires carries its own *fuse*.

Now-a-days the main line also carries a third wire (usually with green insulation) which is called *earth wire*. This wire starts from a deep earth connection in the nearest electric sub-station. Importance of this wire is highest for appliance with metallic body. The metallic body is connected to the "earth" wire. Thus even, if there is a mild leakage of current to the body of the appliance, its potential remains equal to that of the earth and we do not receive the electric shock.

30. A *fuse wire* or simply *the fuse* is a wire of low melting point inserted in the positive line wire. It is made from an alloy of tin and lead (Tin 63% + lead 37%).

The thicker the fuse wire, the greater is its capacity. Thus fuse wires of various capacities are available

QUESTIONS

[A] Objective Type Questions :

1. Complete the following :

(*a*) 1 volt = ... joule per . (*b*) 1 mV = ... V (*c*) 1 μV = ... V ....

(*d*) 1 kV = ... V (*e*) 1 MV = ... V (*f*) Q = ... × t.

2. The work needed to move an electric charge between two points is measured in units known as

(*a*) coulomb (*b*) Watts (*c*) joules (*d*) amperes.

3. Most metals are good conductors of electricity because they have

(*a*) a large number of molecules. (*b*) a large number of free electrons. (*c*) a shiny surface.

(*d*) a low temperature.

4. Six joules of work is required to transfer 12 coulombs between two points. The potential difference, in volts, between the two points is

(*a*) 0·5 (*b*) 2 (*c*) 12 (*d*) 72.

5. The S.I. unit of electric potential is the

(*a*) volt (*b*) joule (*c*) coulomb (*d*) newton.

6. Solids which are good conductors of electricity have many loosely bound

(*a*) protons (*b*) electrons (*c*) atoms (*d*) neutrons.

7. A unit of electric current is the

(*a*) volt (*b*) watt (*c*) ampere (*d*) coulomb.

8. To keep an electric current flowing through a conductor, it is necessary to maintain

(*a*) the potential difference between its ends.

(*b*) the capacity of the conductor

(*c*) the quantity of charge

(*d*) the ratio between potential difference and charge.

9. A 30 ohm and a 60 ohm resistors are connected in series. The current in the 60 ohm resistor is how many times that in the 30 ohm resistor ?

(*a*) 1 (*b*) 2 (*c*) 1/2 (*d*) 4.

10. A 30 ohm and a 60 ohm resistor are connected in series. The combined resistance of the two resistors, in ohms, is

(*a*) 20 (*b*) 90 (*c*) 30 (*d*) 1800.

11. The current in a 60 ohm resistor connected to a battery of negligible resistance having an emf (P.D.) of 30 volt is ....

12. The voltage across a resistor of 20 ohm, with a current in it of 3·5 ampere — —

13. A 20-ohm and a 40-ohm resistor are connected in parallel. The current in the 40-ohm resistor is how many times that of the 20-ohm resistor ?

(*a*) 1 (*b*) 2 (*c*) 4 (*d*) 1/2.

14. If the potential difference across a resistor is doubled, the current in it is

(*a*) unchanged (*b*) doubled (*c*) halved (*d*) quadrupled.

15. As more appliances are added in parallel to a battery of negligible internal resistance, the voltage across each appliance

(*a*) increases (*b*) decreases (*c*) remains the same.

16. Two charged bodies *A* and *B* are at potential —30 V and + 20 V respectively and they are connected by a conducting wire, The current

(*a*) will flow from *A* to *B* (*b*) will flow from *B* to *A* (*c*) will not flow at all.

17. A charge of 120 coulomb flows acrdss a point in 4 minutes. The flow of an electric current, in ampere is.

(*a*) 5 (*b*) 0·5 (*c*) 1/5 (*d*) 25.

18. A 2-ohm resistor and a 4-ohm resistor are connected in parallel. The combined resistance of the two resistors, in ohm, is

(*a*) 13·3 (*b*) 133 (*c*) 1·33 (*d*) 1330 (*e*) 0·133.

19. The unit of specific resistance is

(*a*) ohm-metre (*b*) ohm (*c*) volt (*d*) ampere

20. 1 volt of potential difference is equal to

(*a*) 1 coulomb per joule (*b*) 1 joule (*c*) 1 joule per coulomb (*d*) 1 ampere per joule

21. A 20-ohm and a 40-ohm resistor are connected in series. The ratio of the power used by the 40-ohm resistor to that used by the 20-ohm resistor it

(*a*) 1 (*b*) 2 (*c*) 1/2 (*d*) 4.

22. A 20-ohm and a 40-ohm resistor are connected in parallel. The power used by the 40-ohm resistor is how many times that of the 20-ohm resistor ?

(*a*) 1/2 (*b*) 2 (*c*) 1/4 (*d*) 4.

23. For the resistors in Q. 22 the rate at which heat is developed in the 40 ohm resistor is how many times that the 20-ohm resistor ?

(*a*) 1/2 (*b*) 2 (*c*) 1/4 (*d*) 4.

24. If a potential difference across a resistor is doubled, the power used by it is

(*a*) unchanged (*b*) doubled (*c*) halved (*d*) quadrupled.

25. Several electrical appliances are arranged in order to decreasing wattage rating. Assuming that they are rated at 120 volts, as the wattage rating decreases, the resistances of the appliances

(*a*) increases (*b*) decreases (*c*) remains the same.

26. A 100-watt heater operates on 120 volts. The current in the heater is ...... amperes.

27. Of the following, the meter which reads energy used, is the

(*a*) ammeter (*b*) voltmeter (*c*) ohm meter

(*d*) kilo-watt-hour meter.

28. $3{\cdot}6 \times 10^6$ joules of energy represent

(*a*) watt-hour (*b*) kilo-watt-hour (*c*) watt (*d*) H.P.

29. When a current of I amperes flows through a resistor of R ohms, the rate of production of heat is

(*i*) I^2R joule per second (*ii*) I^2R watt (*iii*) I^2R coulomb per volt.

30. The following electromagnets have the *same* core. Which one is the strongest ?

(*a*) 100 turns and 3 amperes (*b*) 200 turns and 2 amperes

(*c*) 50 turns and 7 amperes.

31. Electrons are projected perpendicularly into a magnetic field. As the speed with which the electrons are projected increases, the force on the electron.

(*a*) increases (*b*) decreases (*c*) remains the same.

32. If an ammeter is to be used to measure the current in a circuit, it should be connected in ________ with the circuit.

33. In household wiring, a parallel circuit is preferred because

(*a*) if one line is overloaded, the fuse in this circuit only will be blown off and other distribution lines are protected

(*b*) if one line is overloaded all the fuses will be blown off and other distribution lines are not protected

(*c*) there is no uniform potential difference across each line.

34. In electrical terminology, *earthing* is a conductor connected

(*a*) to the earth (*b*) to an insulator (*c*) to a tree (*d*) None of these.

35. A safety fuse must be connected in series with

(*a*) live wire (*b*) earth wire (*c*) neutral wire.

36. Complete the following :

(*i*) The magnetic field is largest where the field lines are ......

(*ii*) If a positive charge experiences a magnetic force straight up, a negative charge moving in the same direction will experience a magnetic force ....

(*iii*) The magnetic force on a current-carrying wire is zero when the magnetic field is ...... or .... to the current

(*iv*) A nearly *uniform* magnetic field can be found inside a ....

(v) The direction of the magnetic field due to a straight conductor carrying current is given by ....rule.

37. The work done in moving a unit positive charge across two points in an electric circuit is a measure of

(a) current (b) potential difference (c) resistance

(d) power.

38. The device used for measuring potential difference is known as

(a) ammeter (b) voltmeter (c) galvanometer

(d) potentiometer (e) ohm-meter.

39. Electromagnetic induction is involved in

(a) charging a body with a positive charge.

(b) production of current by relative motion between a magnet and the coil.

(c) rotation of the coil of an electric motor.

(d) generation of magnetic field due to a current carrying solenoid.

40. An electric generator actually acts as

(a) a source of electric charge (b) a source of heat energy

(c) an electromagnet. (d) a converter of energy.

[B] Very Short Answer Type Questions :

1. What property do electrical objects have ?

2. What is Coulomb's law of charges ?

3. How does a charge on an electron compare with the coulomb ?

4. What kind of charge is acquired by a neutral object when it touches a positive object ?

5. Is electric field intensity a scalar quantity ?

6. What is one ampere ?

7. What does the electric current consist of in metals ?

8. State ohm's laws.

9. What is one ohm ?

10. What is a milliampere ?

***11.** What is the effect of each of the following on the resistance of a metallic conductor

(a) doubling the length

(b) doubling the cross-section area

(c) increasing the temperature.

12. What is meant by a closed circuit ?

13. What is the potential difference across one of the resistors in a series circuit ?

14. What is the combined resistance of resistors connected in parallel ?

15. What is a voltmeter ? How is it connected in an electrical circuit ?

16. What is an ammeter ? How is it connected in an electrical circuit ?

17. Name the S.I. unit of

(a) charge (b) current (c) potential difference

(d) resistance.

18. What is the relationship between coulomb and ampere ?

19. How is the energy used by a device related to its power rating ?

20. If two unequal resistors are connected in parallel, which resistor develops heat at the greater rate ?

21. Name three appliances which are based on the heating effect of current.

22. Name the S.I. unit of

(*a*) Electrical energy (*b*) Electric power (*c*) Electrical energy used.

23. How are electrical appliances connected in a house ?

24. What is earthing ?

25. Define volt.

26. What is bigger, a coulomb or charge on an electron ?

27. How many electronic charges form one coulomb of charge ? Charge on an electron is -1.6×10^{-19} coulomb.

28. Two bodies having one coulomb of charge each is separated by 1 m in air. What is the force of repulsion between them ?

29. Define : Ohm

30. Can a magnet have an isolated pole ?

31. Where can we find a magnetic field ?

32. If we represent a magnetic field by lines of force, how do we differentiate between a strong and a weak field ?

33. When a straight wire carries current, what is the shape of the magnetic field that is produced by the current ?

34. How can the direction of the magnetic field in Q. 33 be determined ?

35. If a circular wire loop carries current, why is there a relatively strong magnetic field in the centre of the loop ?

36. How can we find the north pole of a solenoid if we know the direction of current flow in it ?

37. What determines the strength of a solenoid ?

38. Under what conditions does an electric charge produce a magnetic field ?

39. Does a spinning electron behave like a magnet ?

40. What is an ammeter ?

41. What is a voltmeter ?

42. What is an electric generator ?

43. A charge is lying at rest in a magnetic field. What is the force experienced by it ?

44. Will a compass needle when placed near the north pole of a magnet experience a force ? Why ?

45. Two parallel wires carry current in the *same* direction. Will they attract or repel each other ?

46. A straight wire carrying current produces a magnetic field around it. State the rule which determine the direction of the magnetic field produced.

47. How are electrical appliances connected in a house ?

48. What is earthing ?

49. What is the material of a fuse wire? Is the melting point of a fuse wire low or high ?

50. Usually three insulated wires of different colours are used in an electrical appliance. Name the three colours. [*A.I.S.S.1987*]

[C] Short Answer Type and Essay Type Questions :

1. State coulomb's law of force of interaction between two charges and hence define coulomb (a unit charge). [*A.I.S.S. 1982*]

2. (*a*) Define : Electric field and Electric field intensity.

(*b*) Is electric field intensity a vector or a scalar quantity ?

(*c*) Mention its unit in SI system.

(*d*) Derive an expression for the magnitude of electric field intensity at a point in an electric field.

3. What determines whether a difference of potential exists between two points ?

(*b*) Define (*i*) potential difference

(*ii*) volt

(*c*) Is potential (or potential difference) a vector or a scalar quantity ?

(*d*) A conducting object connected to the earth is at zero potential. Explain.

4. Derive an expression for the amount of heat produced in a conductor when an electric current flows through it.

5. What is meant by power and energy in an electric circuit ? How are these measured ? What is meant by one unit of electricity.

6. Define ; watt, kilowatt-hour and kilo-watt.

7. Distinguish between conductors and insulators.

8. Name three quantities that are measured in electricity and state in what units they are measured.

9. (*a*) Define : Electric potential difference ; Electric current ; an ampere ; coulomb ; volt and ohm.

(*b*) What is the relationship between charge and current ?

(*c*) Complete the following :

(*i*) 1 coulomb = ...electrons

(*ii*) 1 m A = ...A

(*iii*) 1 μ A = ...A

(*iv*) 1 m V = ...V

(*d*) Explain the meaning of the statement, "Potential difference between two points is 1 volt."

[*A.I.S.S. 1982*]

10. State the use of the following electrical instruments in an electric circuit :

(*a*) Ammeter

(*b*) Voltmeter

(*c*) Rheostat

(*d*) Key

(*e*) Cell or battery

(*f*) Connecting wires.

11. Draw the following circuit :

A battery of 3 cells supplies current to a circuit in which a given wire is connected in series with a lamp, a rheostat (variable resistance), a plug key and an ammeter ; a voltmeter is now connected across the given wire to measure the potential difference between its ends.

12. State Ohm's Law. Draw an electrical circuit with which you can verify this law and make out a table showing the readings required for this experiment. Name two physical conditions that influence the resistance of the conductor.

13. (*a*) Define resistance of a conductor. Mention its unit and define it also.

(*b*) What is the difference between a rheostat and a resistance box ?

14. Calculate the total resistance when a number of conductors are joined

(*a*) in series, and

(*b*) in parallel.

15. (*a*) What is an electric circuit ?

(*b*) If one bulb gets fused in your house, will other bulbs remain glowing ? Why ?

(*c*) Write down the full names and nationalities of the scientists after whom the following units are named.

The ampere : the volt ; the ohm. (Find these out from books in your school library.)

16. Connect two lamps (each 1.5 *V*), a battery (1·5 *V*) and a switch so that one lamp remains permanently alight and the other lamp be switched on and off by the switch.

17. Connect the two lamps, two switches and a battery so that both switches are required to switch on both lamps, but one switch will switch off one lamp and other switch will switch off both lamps.

18. (*a*) Mention the various factors that affect the resistance of a conductor.

(*b*) What do you understand by the specific resistance (or resistivity) of the material of conductor ?

(*c*) State SI unit of specific resistance of a conductor.

19. (*a*) How does the resistance of a conductor vary with its length ?

(*b*) What is the relationship between the resistance of a conductor and its cross-sectional area ?

20. The resistance wire in an electric radiator is usually wound on fireclay an insulating material ? Why is an insulating material used ? What would happen if a bare resistance wire were wound on a piece of iron ?

21. Some materials conduct electricity ; for example piece of iron or copper. Others like paper, do not appear to conduct, and we call them insulators. Wood is an insulator. It might be a good material on which to wind the resistance wire of the electric radiator element, but it is not. Why not ?

22. Why does the resistance wire get hot and not the copper wire of the cable of the electric immersion heater ?

23. (*a*) Define an electric line of force.

(*b*) Give the chief properties of electric lines of force.

(*c*) Explain the electrostatic attraction and repulsion on the basis of the lines of force.

(*d*) Why two electric lines of force do not cross each other ?

24. A very small sphere is given a positive charge and is then brought near a large negatively charged plate. Draw a diagram of the system showing the appearance of the electric lines of force.

25. How can you explain (*a*) the presence of a charge on a glass rod after it has been rubbed with silk, (*b*) the charge remaining on the silk ?

26. (*a*) What is a magnet ?

(*b*) Define : pole a magnet ; Magnetic axis of a magnet.

(*c*) What is the difference between an electromagnet and a permanent magnet ?

27. (*a*) What is a magnetic field ?

(*b*) Can two lines of magnetic force intersect with each other ?

28. (*a*) Can a magnetic field be seen ?

(*b*) Can it be detected ?

(*c*) Can a magnetic field be mapped out ?

29. Show by a simple experiment that when current flows inside a wire, a magnetic effect is noticed near it. Mention some rule to determine the direction of the field.

30. (*a*) Discuss the field pattern due to

(*i*) straight current-carrying wire,

(*ii*) a circular coil carrying current, and

(*iii*) a solenoid.

Draw clear diagrams to explain the chief features of the magnetic fields, (*A.I.S.S. 1982*)

(*b*) Explain right-hand rule to determine the direction of the field in each case discussed in (*a*).

31. What is a Solenoid ? How will you show that a solenoid carrying current behaves like a bar magnet ? Describe the rule for determining the polarity of the ends of the solenoid.

32. (*a*) What is an electromagnet ?
(*b*) Draw a diagram of an electromagnet. Explain how it works.
(*c*) Give a brief account of some of the important practical applications of an electromagnet.

33. We can increase the lifting force of an electromagnet by :
(*i*) increasing the current ;
(*ii*) increasing the number of turn of wire ;
(*iii*) increasing the cross-sectional area of the core ;
(*iv*) making the core of glass instead of soft-iron.

Choose one answer from above which is not correct.

34. (*a*) State Fleming's Left Hand Rule and illustrate it by two examples. (*A.I.S.S. 1982*)
(*b*) How can you demonstrate Fleming's Left Hand Rule Experimentally ?

35. The magnetic field at a point associated with a current carrying conductor is
(*i*) directly proportional to the current flowing ;
(*ii*) directly proportional to the distance from the conductor ;
(*iii*) inversely proportional to the current flowing ;

Choose the correct answer.

36. (*a*) What do you know of the action of magnetic field on a conductor carrying a current ?
(*b*) A wire BA of length (Fig. 9. 91) is placed vertically between the poles of a large magnet having magnetic field B tesla. It is free to turn in any direction. State and explain what happens when a current I is passed through the wire in the direction BA. (A is free to move).

What is the expression for the mechanical force experienced by the wire carrying current ?

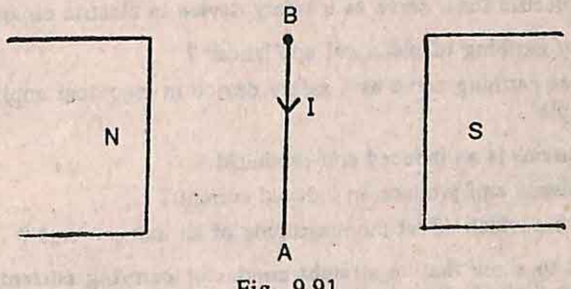

Fig. 9.91

37. If the direction of a current in a conductor is towards the reader but out of the pages, is the direction of magnetic field (*Choose one answer*)
(*i*) along the conductor towards the reader ?
(*ii*) clockwise around the conductor ?
(*iii*) counter-clockwise around the conductor ?
(*iv*) along the wire into the page.

38. A straight conductor is placed parallel to the magnetic field of a magnet. Will it move in any direction when a current is passed in it ? Give your reasons.

39. (*a*) Give the unit of magnetic field in SI system and define it.

(*b*) How tesla and gauss are related to each other ?

40. Copy Fig 9. 92 and put in an arrow showing which way the coil (free to turn about a vertical axis) tends to move.

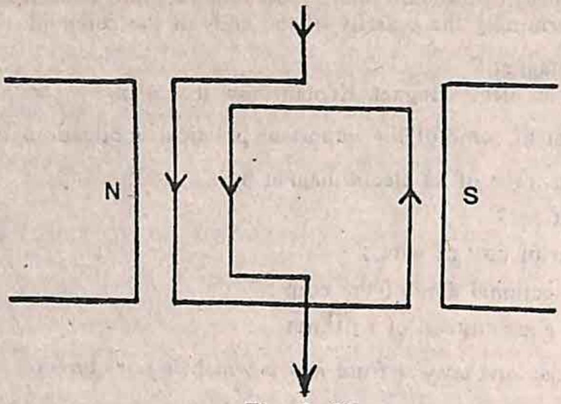

Fig. 9. 92

41. (*a*) What is magnetic field (B) ?
(*b*) Does a small magnetic needle experience a force when placed in the magnetic field of another magnet ?
(*c*) Is the magnetic field (B) a scalar or vector quantity ?
(*d*) Does an electron at rest experience a force in a magnetic field ? Name two factors that influence the force experienced by a current carrying conductor in a magnetic field.

42. Why cannot one obtain an isolated north pole by breaking a magnet into two pieces ?

43. Write a short note on household electric circuits. Why is a parallel circuit preferred ?

44. (*a*) What is an electric fuse ?
(*b*) Why does fuse contain tin and lead ?
(*c*) Outline how you would demonstrate the action of a fuse wire in a circuit.
(*d*) Why is it dangerous to replace a fuse with an iron nail ?
(*e*) In what way do electric fuses serve as a safety device in electric circuits ?

45. (*a*) What is meant by earthing of electrical appliances ?
(*b*) In what ways does earthing serve as a safety device in electrical appliances ? Explain with the help of an example.

46. (*a*) Under what conditions is an induced emf produced ?
(*b*) When does an induced emf produce an induced current ?
(*c*) What are the factors which affect the magnitude of an induced emf ?

47. Describe an experiment to show that a straight conductor carrying current placed in a magnetic field experiences a force and that the direction of force depends on the direction of (*i*) the magnetic field, and (*ii*) the current.

48. (*a*) What is an electric generator ?
(*b*) What are the important parts of an A.C. generator ? Draw a labelled diagram. What is the function of each of these parts ?
(*e*) Explain the principle underlying the working of an A.C. generator.
(*d*) Why does the direction of the induced current in the coil change after every half revolution.

49. What is the essential difference between

(*a*) alternating current (A.C.) and direct current (D.C.) and (*b*) A.C. generator and D.C. generator.

What is the frequency of A.C. in India ?

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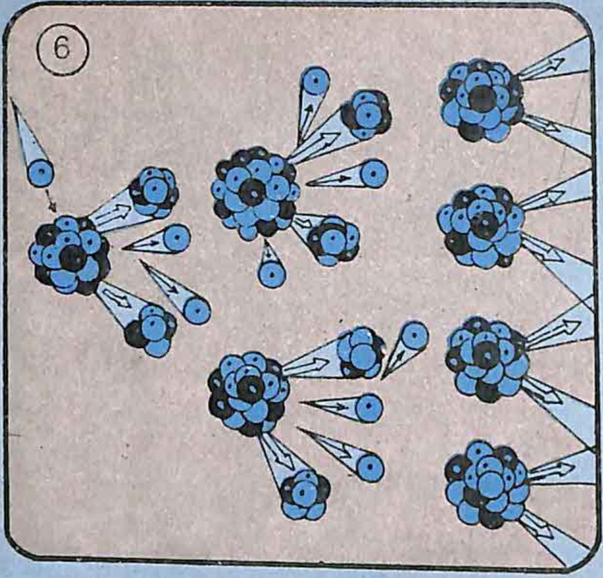

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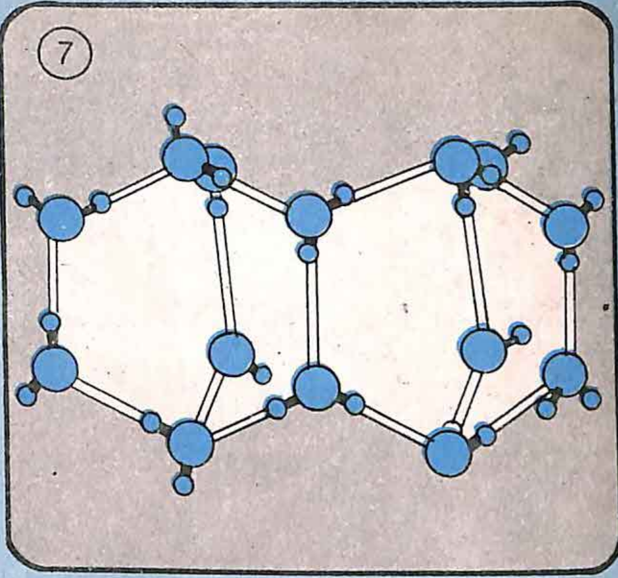

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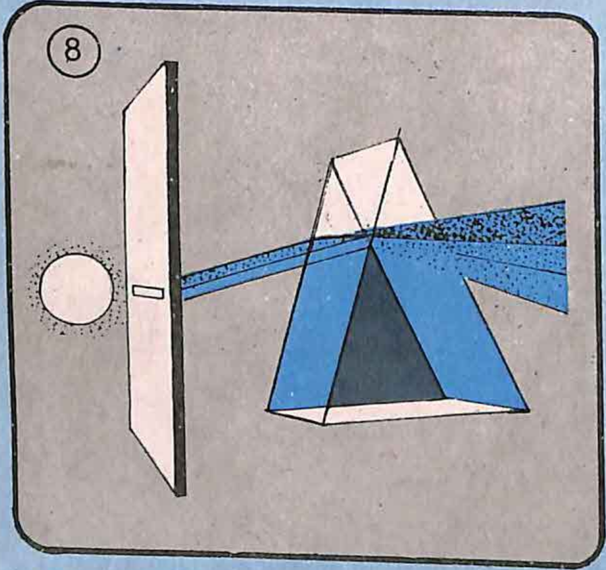

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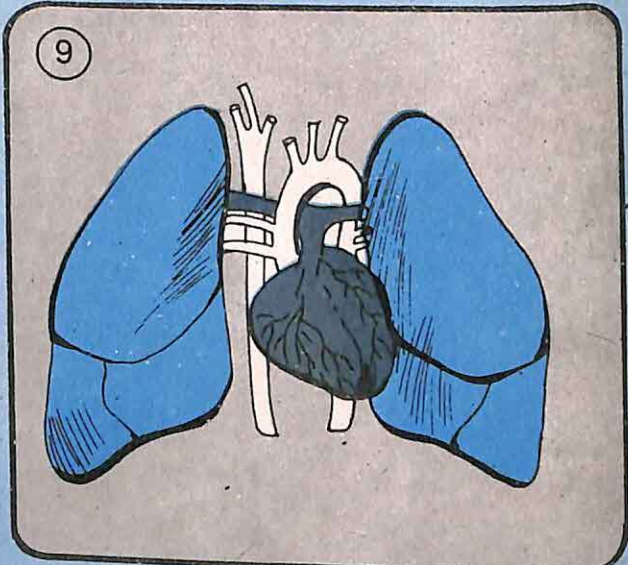

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